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HERBICIDAL USE OF CARBON DISULFIDE

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INTRODUCTION

Carbon disulfide is recognized as an effective herbicide for controlling deep-rooted perennial weeds. A clear, volatile liquid, it readily vaporizes to produce a gas highly toxic to plant tissues. When it is injected beneath the soil surface, its vapors diffuse through the air spaces, destroying all plant structures they may contact within the soil.

The chief herbicidal value of carbon disulfide lies in its use against such weeds as wild morning-glory (*Convolvulus arvensis* L.), hoary cress, or white top (*Lepidium* and *Hymenophysa* spp.), Russian knapweed (*Centaurea repens* L.), poverty weed (*Iva* spp.), and burweed (*Franseria*). It has also been successfully employed in the control of such shallow-rooted perennials as Bermuda grass (*Cynodon Dactylon* [L.] Pers.) and quackgrass (*Agropyron repens* [L.] Beauv.). It has occasionally been used against Johnson grass (*Sorghum halepense* [L.] Pers.), ragweed, willows, and many other less noxious species.

Carbon disulfide, as a weed killer, has no deleterious effect upon the soil, a distinct advantage on intensively cropped land. Some is lost by diffusion; the remainder is eventually decomposed and oxidized to sulfate. Stimulated crop production often follows the treatments. This fact indicates that partial soil sterilization may result from the vapors. If straight carbon disulfide is applied, the soil may be safely seeded within 6 to 8 weeks. This chemical is classed, therefore, as a temporary soil sterilant, in contrast to arsenic compounds, which affect the soil for several years. Sodium chlorate, ammonium sulfamate (Ammate), ammonium thiocyanate, and boron compounds are also temporary sterilants; but, in comparison with carbon disulfide, they have more lasting effects upon the soil.

HISTORICAL REVIEW

Carbon disulfide was used as an insecticide as early as 1854 by Garreau (Simmons and Ellington, 1926)[7] for fumigating stored grain. As a soil fumi-

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[1] Received for publication April 2, 1945.

[2] As used in this publication, the term *carbon disulfide* refers to the technical product supplied by chemical manufacturers for use in fumigation and in weed and rodent control. In California this product is obtainable from Wheeler, Reynolds & Stauffer under the designation of "Anchor Brand." This company also manufactures "Activated Carbon Bisulfide," composed of the technical grade of carbon disulfide plus an amendment that lowers its vapor pressure. This material is sold exclusively for weed killing. The added amendment may have a fairly prolonged sterilizing effect upon the soil under certain soil and climatic conditions. Anchor Brand does not have this residual effect. (For further discussion of this subject see p. 51.)

[3] The studies described herein were inaugurated and directed by the College of Agriculture, Division of Botany. The work was supported by funds contributed to the California Agricultural Experiment Station by Wheeler, Reynolds & Stauffer.

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[6] Associate Professor of Botany and Associate Botanist in the Experiment Station.

[7] See "Literature Cited" for complete data on citations, referred to in the text by name of author and date of publication.

gant it was recommended by Thenard in 1869 (Fleming and Baker, 1935). Controlled dosages applied in vineyards during the dormant season were found to kill phylloxera without undue injury to the vines.

Many later investigations proved the value of carbon disulfide as a general soil fumigant for controlling soil-inhabiting insects, fungi, and nematodes. Incidental to these studies and to many commercial treatments have been observations of the effects of the toxic vapors upon the roots of higher plants. Marion (1878) and other workers on phylloxera found that injections must be kept a certain distance from the vine; direct contact of the liquid with roots is usually fatal. Carbon disulfide emulsions, which are less toxic than straight carbon disulfide, are now commonly employed against insects, garden centipedes, and nematodes in planted areas.

Though known to be toxic to plants, carbon disulfide was first used as a herbicide by Walker (1906), who poured the liquid around the stems of sassafras and killed them in an apple orchard. Wilcox (1909) subsequently used the same method on sassafras in Maryland; later, on guava, lantana, prickly pear, and other weeds in Hawaii. Control of wild morning-glory by carbon disulfide in November, 1913, was reported by Horticultural Commissioner Thomas Beers (1913) of Santa Barbara County, California. The following month J. C. Loomis (1913), writing in the *Pacific Rural Press,* reported the success of treatments on morning-glory and other weeds at Irvington, California. Beers advised using a prod to make holes for injection, whereas Loomis employed a short-handled hoe to dig a hole for application to each individual plant. Injections were closely spaced and shallow.

In 1919 Thomas Mayhew initiated experiments in Monterey County. His method (Barnum, 1923) involved treating dry soil by making holes 3 feet apart each way and applying 4 ounces of the liquid in each hole to a depth of 18 inches. Later, Hickman (1922) recommended 2-ounce injections in holes 18 inches apart each way and 16 inches deep. In an experiment on Russian knapweed, reported by Johnson (1923), part of the infestation was treated with 4 ounces per injection in holes 18 inches apart each way and 18 inches deep; and part was injected with 4 ounces per hole in holes spaced 30 inches apart in 18-inch rows and 12 inches deep. When both treatments proved successful, Johnson concluded that the lower dosage was sufficient and that soil conditions as well as the habits of the weed should be considered. Apparently, therefore, the method of application was not critical, provided a proper dosage was applied.

By 1925 the procedure in California seemed fairly standardized, for Johnson (1925) described the common method as application by hand in holes 18 inches apart and 12 to 18 inches deep at a rate of 2 ounces per hole. Three years later, the holes were being made 18 to 24 inches apart and 6 to 8 inches deep (Johnson, 1928). On packed roadside soils the distance between holes was reduced to 12 to 15 inches. These values for dosage, spacing, and depth have since persisted in California. Thousands of carloads of carbon disulfide have been applied in California and throughout the western states with generally good results. The chief questions concern the occasional failures after the use of a uniform dosage in soils of widely varying properties and against weeds of differing character. Some of the results that brought up these questions will be listed.

Frost (1932), using a mechanical injector (a metering pump on a subsoiler), obtained 95 to 100 per cent control with dosages equivalent to 3 ounces spaced 20 by 27.4 inches and 4½ ounces spaced 30 by 27.4 inches. An Idaho recommendation in 1926 (Ayres, Hulbert, and Ahlson, 1926) states (in contrast to Mayhew's opinion) that the soil should be moist. Excellent control was obtained on some areas treated during a summer rain and already saturated with moisture. Two-ounce injections were made in holes 18 inches deep and 24 inches apart.

By 1934 the method in Idaho had changed to a 6- to 8-inch depth with 2 ounces per hole at 18- to 20-inch spacings. Spence and Hulbert (1935) proposed a 6- to 8-inch depth for white top (hoary cress) and quackgrass; 8 to 10 inches for other weeds. In 1937, Spence recommended a 6-inch depth for all weeds except morning-glory, which was to be treated 8 inches deep.

In Utah (Peterson and Tingey, 1928), treatments in moist soil were best, with failures occurring in dry soils. Rogers (1928) in Colorado, however, obtained his best results in rather dry soil. Rogers and Hatfield (1929) used 2-ounce doses in holes 2 feet apart each way and 18 inches deep in heavy soils, 12 inches in sandy ones.

Most of the early work with carbon disulfide was done in spring, summer, and early fall, failures being reported from winter treatments. In 1937, however, treatments made through frozen soil in late 1936 were observed in Idaho. Complete kills were obtained. Recent reports from eastern Oregon indicate similar results. Furthermore, injections to only 4 inches have proved successful on shallow-rooted perennials in moist soil where the surface was well sealed by tamping or rolling. Bermuda grass has been killed by surface sprinkling, followed by covering with waterproof paper or wet canvas; also by covering quickly with 2 to 4 inches of soil.

Since treatments have succeeded where dosage, depth, spacing, soil moisture, and season have varied so widely, evidently not one but many factors determine the effectiveness of a given treatment. Moreover, any blanket dosage recommendation yielding comparable results under all variations in these factors will necessarily be much above the minimum practical dosage. Money could be saved and failures averted if the relations of these various factors to successful treatment were understood.

Carbon disulfide was soon brought into use against wild morning-glory, one of the most serious weed pests on western farms. In irrigated fields of beans, corn, melons, cotton, and similar summer row crops, however, many morning-glory plants survived the treatment by making new growth from the crown.

After several years of empirical testing by farmers, weed-control supervisors, and sales agents, the general practice was to apply 2-ounce[8] doses in holes spaced 18 inches apart each way and 6 inches deep (see pp. 32 and 53). In well-moistened soils, however, a depth of 4 inches was preferred if the treatment could be followed by careful packing of the topsoil by tamping or rolling. This practice was successful in Idaho, especially in the Snake River Valley. During the 1930's many carloads of carbon disulfide were used in Idaho.

[8] Ounce, as used here and in most of the references, refers to fluid ounce. One fluid ounce equals 29.57 ml. An avoirdupois ounce equals 22.5 ml of carbon disulfide.

But, whereas the *standard* dosage and spacing just described gave satisfactory control under a wide range of moisture and temperature conditions in Idaho, they sometimes failed in California and in certain other regions outside the Snake River Valley. Furthermore, this standard method required application of over 3,000 pounds per acre, at a cost prohibitive for extensive control on any but the most productive soils. When the present project was undertaken, three questions were uppermost: Why does the standard carbon disulfide treatment fail in certain isolated cases? How can this trouble be remedied? Are there any conditions under which this chemical will control perennial weeds at lesser dosage rates?

A survey of the irrigated farming region in the Snake River Valley revealed one very interesting point—namely, that this whole region was occupied by only one soil series, consisting mainly of loam or fine sandy loam. This soil, a loess, is made up of gritty particles fairly uniform in size, and has a low content of clay. Carbon disulfide gives effective results in this soil at any time of year, even when injected in winter. The only requirement seems to be that the surface be firmly packed to seal in the vapors after application. Since sealing is most easily accomplished when the soil is moist, the usual practice has been to irrigate a few days in advance and to treat as soon as the soil is in the proper condition for seedbed preparation.

The first plot experiments conducted at Davis were designed to test the effects of soil moisture on the results of carbon disulfide treatment. Plots having a heavy stand of wild morning-glory on Yolo loam were scalped[9] in midsummer of 1935, mulched, and treated with a hand applicator. One series was then sprinkled immediately with water to provide about 2 inches of soaked soil on the surface; the remaining plots were tamped at the points of injection, but not otherwise treated. The subsoil in all the plots at the time of the application was near the permanent wilting percentage, and the topsoil was air-dry. Although the sprinkling brought up many seedlings[10] that had to be hoed repeatedly, control on the sprinkled plots was practically perfect the following spring, whereas that on the dry plots was not above 80 per cent. Evidently, although the sealing of the surface by sprinkling gave excellent results, recent irrigation as by flooding was not a prerequisite to successful treatment.

Plot tests the next year (1936) gave fair control on dry plots, but failed on recently irrigated ones. The irrigated soil had been repeatedly disked for several years, but not deeply plowed. Its wet cultivator sole[11] was apparently almost completely impervious to carbon disulfide vapor.

The following winter (1936–37), the plots were plowed to a depth of 12 inches, to break up the cultivator sole. Repetition of the plot tests the following summer gave different results. Applications were made in September, 1937; readings taken August 16, 1938, are visual estimates of resprouting expressed as a percentage of stand on untreated control plots. The results (table 1) show that satisfactory control may be had on wet soil provided there is no

[9] The term *scalped,* as used in weed control, refers to a removal of top growth, as by hoeing or by the use of a power-drawn weed knife.

[10] Morning-glory seedlings can be distinguished from young resprouts of old roots by the presence of typical cotyledons. Resprouts did not appear upon the sprinkled plots during the year of treatment.

[11] See footnotes 14 and 15 for definitions of *sole* and *pan* formation in the soil.

compacted subsurface layer to prevent the vapor from diffusing, and provided the surface layer is well sealed. The poor results on the dry plots of table 1 are attributed to a cloddy condition that made the topsoil practically impossible to seal against loss of vapor.

A similar series of dry plots on a Madera soil that had been deep plowed and disked down to a dust mulch gave almost perfect control of wild morning-glory. Injections were made to a depth of 12 inches. A year after the applications only 3 plants survived on the 12 plots, these being on the plots receiving the 9-pound application. These results indicate that (1) high soil moisture is not essential to success with carbon disulfide, (2) soil moisture at or below field capacity will not prevent successful treatment, (3) plow or cultivator sole definitely restricts diffusion of the vapor in the soil, (4) a wet sole may completely prevent diffusion, and (5) sealing of the surface against vapor loss is essential to success.

TABLE 1

RESULTS OF CARBON DISULFIDE APPLICATIONS ON WILD MORNING-GLORY PLOTS AT DAVIS, CALIFORNIA

(Treated in September, 1937; read in August, 1938)

Spacing and plot no.	Wet (recently irrigated)		Spacing and plot no.	Dry (no irrigation)	
	Application rate per square rod*	Resprouts, percentage of controls		Application rate per square rod*	Resprouts, percentage of controls
	pounds	*per cent*		*pounds*	*per cent*
16½ inches:			16½ inches:		
1	9	1	13	9	80
2	13½	2	14	13½	30
3	18	1	15	18	2
24⅔ inches:			24⅔ inches:		
4	9	2	16	9	80
5	13½	1	17	13½	50
6	18	3	18	18	12
33 inches:			33 inches:		
7	9	2	19	9	80
8	13½	1	20	13½	75
9	18	5	21	18	60
40 inches:			40 inches:		
10	9	5	22	9	80
11	13½	2	23	13½	60
12	18	2	24	18	25

* The standard dosage of 2 ounces per injection at 18-inch spacings is equivalent to approximately 2 gallons, or 20 pounds, per square rod.

Experiments similar to those reported in table 1, but applied to cold wet soil in midwinter, showed that the lower dosages and wider spacings were not satisfactory. Evidently dosages as low as one half the standard, however, could be used in warm, light-textured soils, free from impervious layers and properly sealed on the surface. Dosages up to or above standard were needed where these requirements could not be met; and any treatment might fail if the surface sealing was not satisfactory.

TOXICITY STUDIES

The herbicidal properties of carbon disulfide were studied in an attempt to find general principles upon which to base interpretations of field work. Some of the questions arising in the field are as follows: Does carbon disulfide kill roots through the vapor phase of the soil, or is it dissolved in the soil moisture and absorbed through young roots? Is the vapor absorbed in the upper root system and translocated downward; or does it move down through the soil,

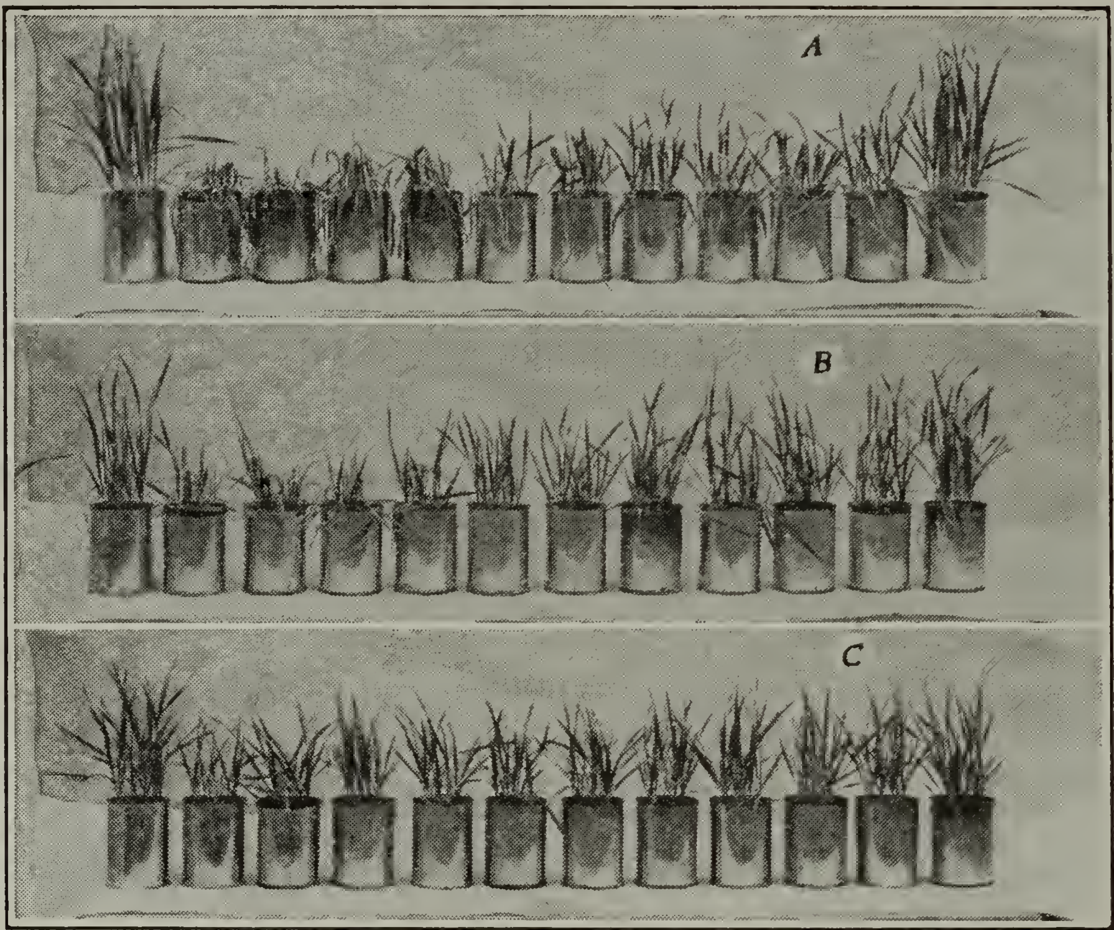

Fig. 1.—Toxicity of carbon disulfide to oats. When the plants were 26 days old, liquid carbon disulfide was injected into the bottoms of the cans. From left to right, the concentrations were 0, 3,640, 2,860, 2,080, 1,560, 1,040, 780, 520, 390, 260, 120, and 0 p.p.m. on the basis of the air-dry soil weight. Toxicity is highest in *A*, Yolo fine sandy loam; intermediate in *B*, Arbuckle clay loam; and low in *C*, Stockton adobe clay. (From Robbins, Crafts, and Raynor, *Weed Control*, by permission of McGraw-Hill Book Company, copyright owners.)

killing as it goes? How rapidly is the root killed, and is the vapor concentration critical? These and other problems were attacked by means of toxicity studies performed in the laboratory and greenhouse.

Figure 1 depicts three series of pot cultures of oat plants that were treated by injecting carbon disulfide into the bottoms of the cans and sealing the soil by wetting on top. As shown in the figure, the tops of the plants receiving heavy dosages soon wilted and died, particularly in the sandy soil. Plants only slightly injured by the carbon disulfide vapor recovered; only those whose roots were actually killed showed permanent injury. Wilting and death of the tops followed injury to the roots and were merely a secondary reaction to the poison. Carbon disulfide kills roots only by contact.

Cultures in the adobe soil had just as much carbon disulfide applied as did those in the loam and fine sandy loam. The toxicant was apparently adsorbed on the colloids and in that form was less available to the plants.

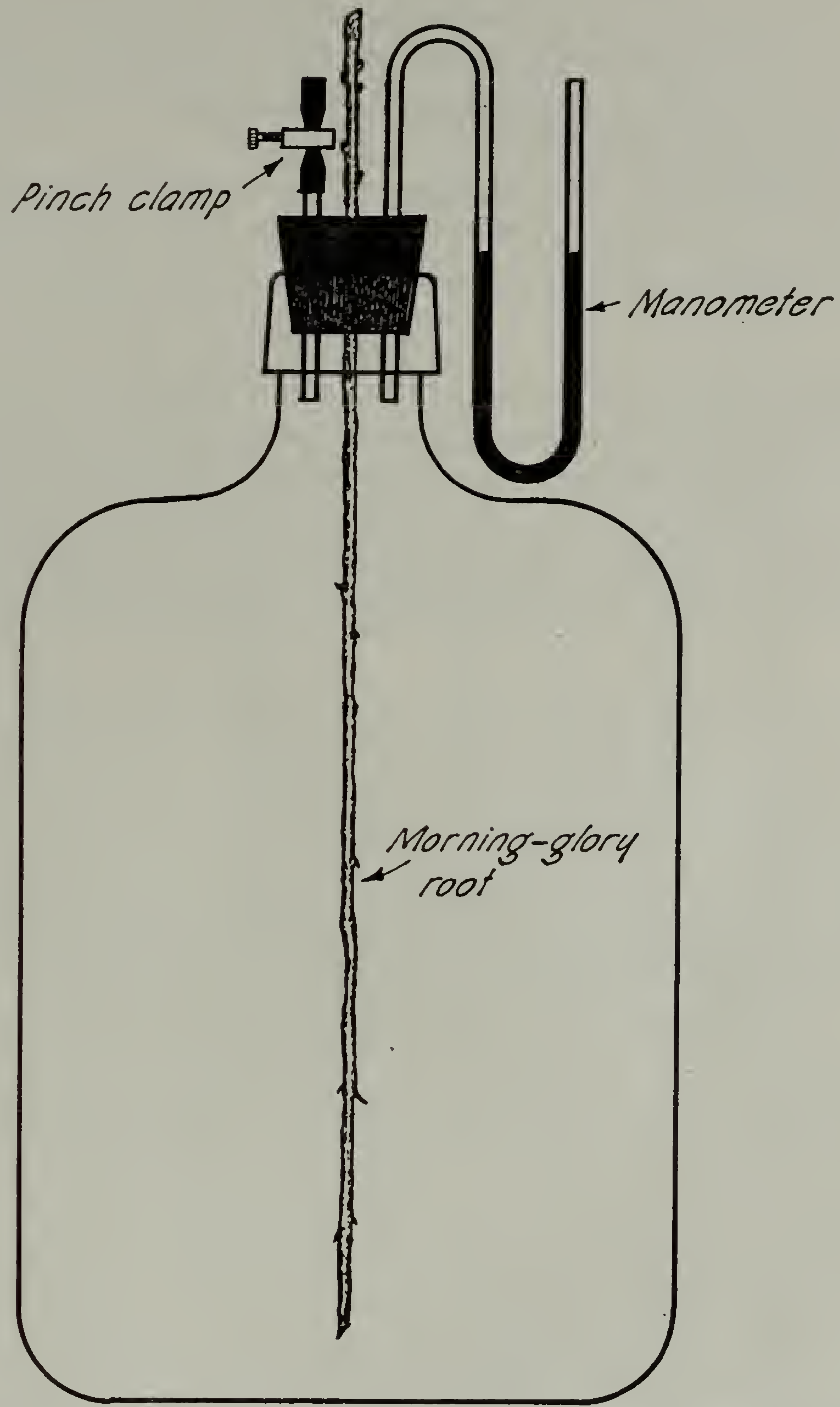

Fig. 2.—Apparatus for treating wild morning-glory roots with carbon disulfide vapor. Each root, suspended through the cork, was exposed to a known concentration of vapor for a given period at a temperature of 20° C.

In later experiments, roots of wild morning-glory were excavated and taken to the laboratory, where they were placed with their lower ends in carboys, their upper ends extending into the air (fig. 2). Each plant was sealed in place in the carboy; the carboy was evacuated until it showed a predetermined subatmospheric pressure; and then enough liquid carbon disulfide was introduced to bring the pressure back to atmospheric as it vaporized. The experiments were conducted at 20° C (approximately 68° F). At varying times

the roots were removed, cut into 3-inch segments, and placed in moist sand in the greenhouse. Readings were made on survival and resprouting.

In other experiments, time of exposure to carbon disulfide vapor and concentration of the vapor were the variables. Table 2 summarizes the results.

These data bring out the important fact that toxicity depends upon both time and concentration. The product of the two gives a constant percentage kill; a product of approximately 240 is necessary for complete killing under the experimental conditions.

Another important fact established was that the carbon disulfide vapor acts strictly as a contact poison. Upper portions of the exposed roots that extended out through the corks into the air survived the treatments at all

TABLE 2

WILD MORNING-GLORY ROOT SEGMENTS KILLED BY EXPOSURE TO CARBON DISULFIDE VAPOR AT THREE DIFFERENT CONCENTRATIONS IN ATMOSPHERE SURROUNDING ROOTS

1 per cent concentration		5 per cent concentration		10 per cent concentration	
Exposure time	Kill	Exposure time	Kill	Exposure time	Kill
hours	*per cent*	*hours*	*per cent*	*hours*	*per cent*
80	40	16	5	8	40
120	50	24	75	12	20
160	80	32	50	16	50
240	100	48	100	24	100
300	100	60	100	30	100

exposure times and all concentrations. There was no evidence that the toxic principle or any secondary products of the killing process were moved out of the region that was in direct contact with the toxic vapor.

MOVEMENT OF CARBON DISULFIDE VAPOR IN SOILS

When liquid carbon disulfide is injected into the soil, it immediately permeates the air spaces in the soil adjacent to the point of injection. At the same time it starts to volatilize, producing a vapor about two and a half times as heavy as air. One might expect this heavy vapor to move downward more rapidly than laterally and upward. Apparently, however, convection is restricted because of soil resistance. For this reason, upward movement almost equals downward, and the pure vapor continues to expand until all the liquid has disappeared. Diffusion occurs only at the outer edges of the pure-vapor phase. When the liquid is all gone, diffusion becomes the chief mode of movement, and the gas spreads at practically the same rate in all directions.

Because of the type of movement that occurs, much carbon disulfide vapor is lost unless the soil surface is well sealed. Especially is this true where the depth of injection is less than 12 inches.

Fleming (1923), studying soil fumigation with carbon disulfide, described asymmetric movement of the vapor in his experiments on prepared soil in a fumigation box. Bywaters and Pollard (1937) and Higgins and Pollard (1937) found similar behavior; but they concluded that vapor movement is largely a simple diffusion process, convection occurring only in coarse-textured or loosely packed soils. O'Kane (1922) reached a similar conclusion.

The fact that the vapor concentration is less above the level of injection than below it must be explained by the rapid surface losses rather than by gravitational or convection flow.

Effect of Soil Factors on Carbon Disulfide Movement.—Soil permeability, involving soil compaction, texture, and moisture, has been recognized as one factor limiting carbon disulfide movement. Gastine, Couanon, and Gastine (1884) pointed out that the physical condition of the soil greatly affects the diffusion of the vapor. In very permeable soils diffusion is rapid, and loss may be excessive. In compact soils diffusion is slow, but the vapors may persist too long for early planting of a crop. The most favorable condition is to have a permeable subsoil, but impervious surface layers. Excess moisture renders clays impermeable, and dryness fosters excessive losses by diffusion from the surface. A rain during or immediately after treatment was found to seal the surface.

Temperature effects also have received attention. According to Fleming (1923), Marion tried to correlate the distance of lateral diffusion with soil temperature, but the variations were so small that he could find no correlation. He did find, however, increased diffusion at high air temperatures. He pointed out the effects of barometric pressure and air temperature upon gas movements in the soil.

Leach (1920) studied the effects of soil temperature under field conditions, but could discover no distinct correlation in spring, summer, and fall.

Laboratory Studies.—The field observations and empirical experiments reviewed in the preceding pages do not indicate the quantitative effects of temperature, moisture, compaction, and textural grade upon carbon disulfide vapor movement in soils. Any evaluation of the relative importance of these factors must rest on fundamental studies under controlled conditions. Such studies have been made by Bywaters and Pollard (1937) and Penman (1940) in England, and by Hagan (1941) and Hannesson (1945) at this Station. The conclusions reached by the English and American workers substantially agree. Only the results on California soils will be reviewed, since they are of immediate interest.

Hagan's (1941) work consisted mainly of the design and use of apparatus for studying gaseous movement through prepared laboratory soils. He employed a constant total pressure and a measured partial-pressure gradient of carbon disulfide vapor through the soil. The apparatus (figs. 3 and 4) consisted of a tube to hold the soil being studied; a shallow dish sealed to the lower end, containing liquid carbon disulfide, from the surface of which the vapor could diffuse; and a manifold fitted to the top, through which air could be slowly drawn to carry away carbon disulfide vapor as it diffused upward through the soil. The air was drawn through absorber columns, where the carbon disulfide was taken out in alcoholic potash solution.

The whole apparatus was set up in an insulated room with accurate temperature control so that experiments could be run at any temperature from 5° to 45° C. Air-dry, pulverized soils were packed into tubes with a compacting machine to a known density and at a measured moisture content. Soils to be run at a moisture content near field capacity were packed air-dry, irrigated, and allowed to stand till the moisture was uniformly distributed. Soils

to be studied at intermediate moisture contents were packed by hand in small increments, each of which was wetted with sufficient water by means of an atomizer. Some intermediate moisture samples were packed dry, irrigated,

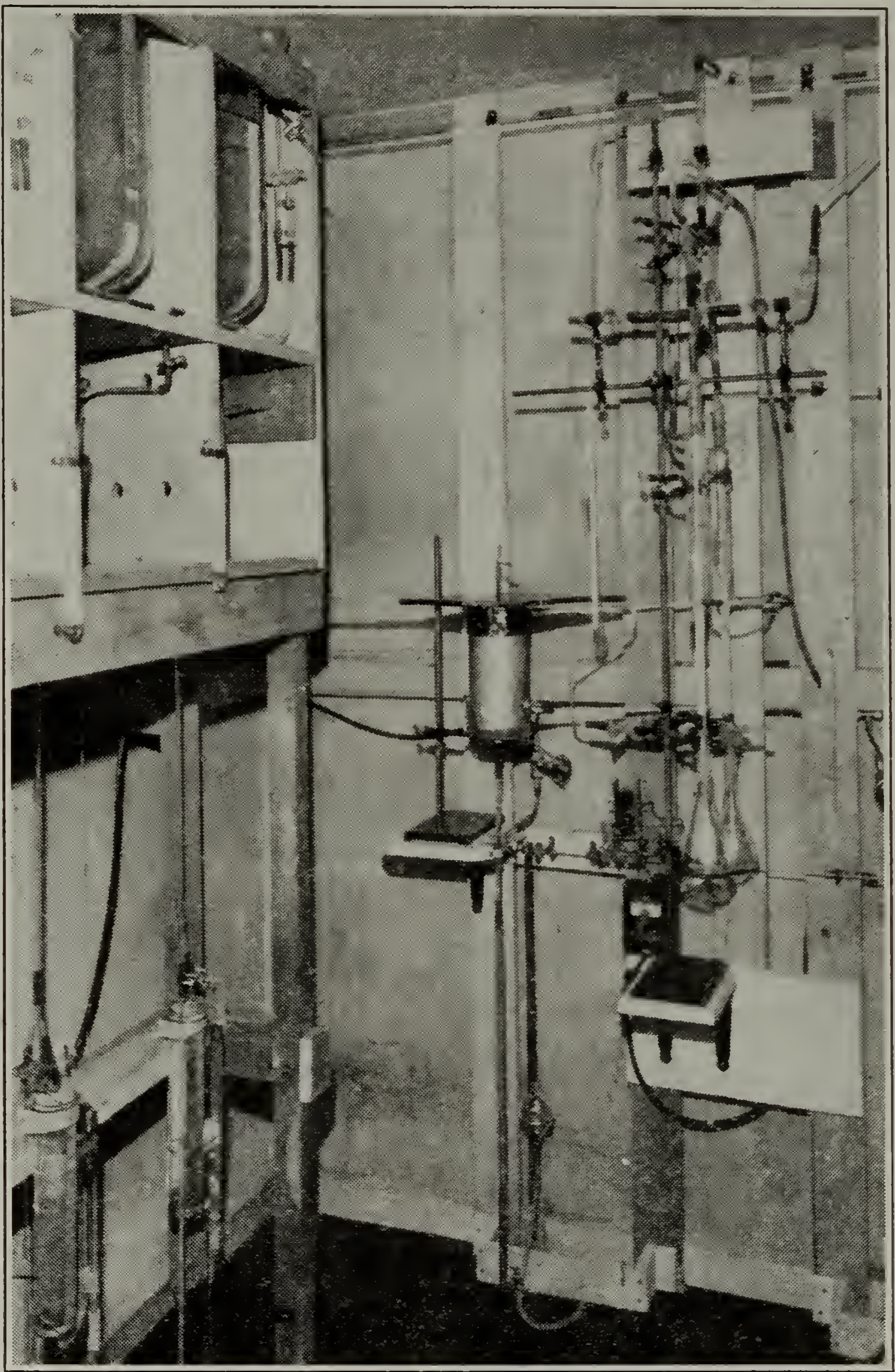

Fig. 3.—General view of apparatus for determining flow of carbon disulfide vapor through prepared soil columns. This apparatus was housed in an insulated chamber with accurate temperature control. (From *Hilgardia* vol. 14, no. 2.)

and then dried by forcing air through the columns until the desired moisture content was attained. Apparatus and methods are described in detail by Hagan (1941).

Temperature.—From a mathematical analysis of his data on diffusion rates in prepared soil columns, Hagan (1941) concluded that the quantity of car-

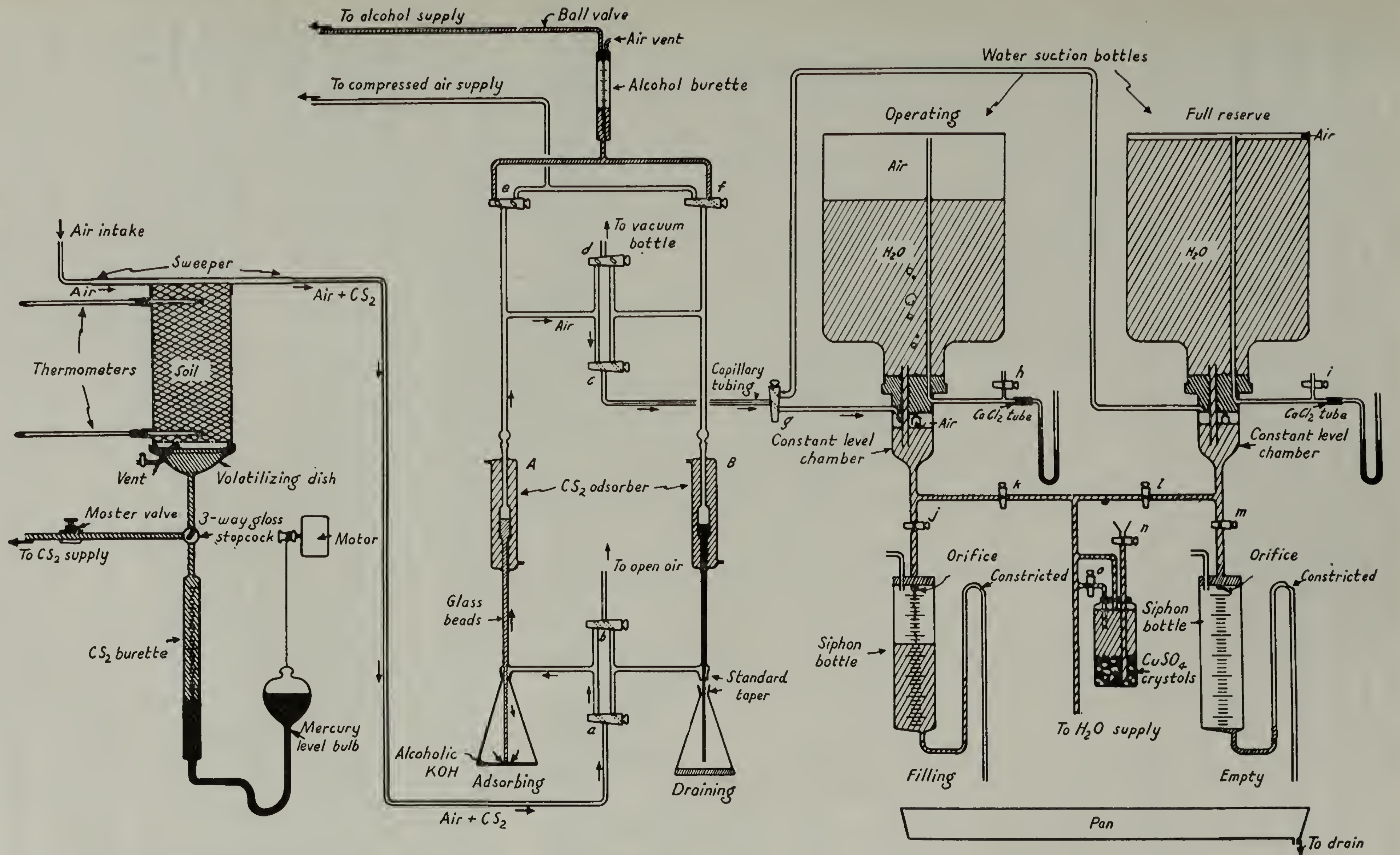

Fig. 4.—Schematic diagram of the apparatus shown in figure 3. The equipment consisted of a soil column in a tube, with means for maintaining a saturated carbon disulfide vapor at its lower end and with a device for carrying the vapor away from the upper end. For satisfactory results the air crossing the top of the column had to move slowly and constantly. It was taken through absorbers, where the carbon disulfide was collected and titrated. (From *Hilgardia* vol. 14, no. 2.)

bon disulfide vapor which will flow through a given volume of soil per unit time is inversely proportional to the viscosity of the vapor, and directly proportional to the difference in carbon disulfide vapor pressure at the two ends of the column. Temperature affects this relation in two ways: First, as a gas is heated, the activity of its molecules is speeded; this decreases its viscosity and raises its vapor pressure. Second, in a closed system, increasing the temperature would simply increase the concentration of vapor; but in a system

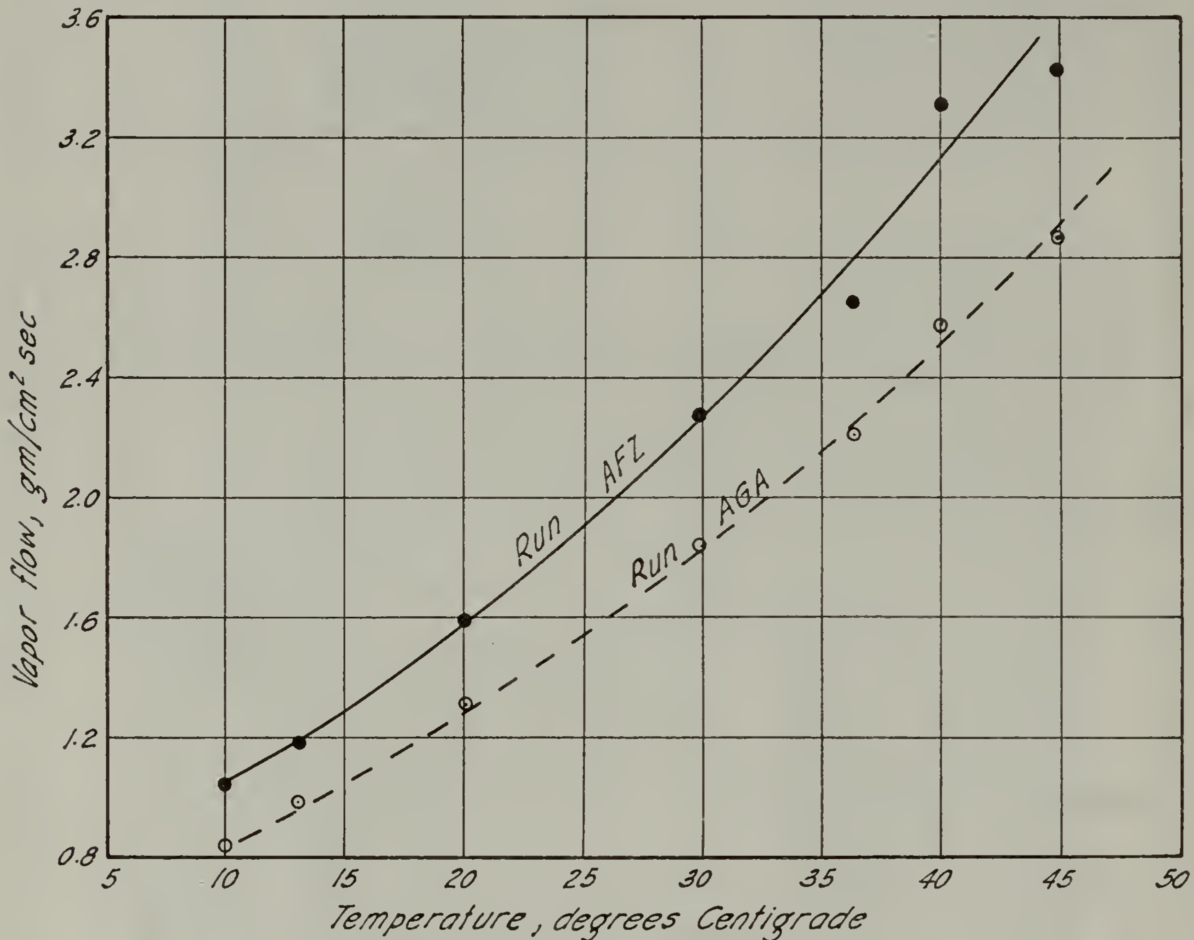

Fig. 5.—Effect of temperature on the flow of carbon disulfide vapor through Yolo fine sandy loam (run AFZ) and Yolo clay (run AGA).

open to a moving air stream at one end, like Hagan's apparatus, increasing the temperature raised the partial pressure of vapor at the bottom end, steepening the vapor-pressure gradient, besides decreasing the viscosity. Hence the rate of vapor flow increased along a rising curve, as is shown in figure 5, prepared from Hagan's data.

From the standpoint of practical soil fumigation, a rise in soil temperature has two effects. First, the rate of both volatilization and diffusion of carbon disulfide in the soil is increased, tending to bring about a rapid and thorough distribution in the soil. Second, losses of carbon disulfide vapor from the soil surface become greater and, unless prevented by surface sealing, may attain serious proportions.

Soil Moisture.—The water content of the soil also influences its permeability to gas movement. The addition of water makes the soil much less porous; at a moisture content somewhat above field capacity, a soil may become almost impervious to gas. Figure 6, taken from Hagan's work, illustrates this point

for Yolo fine sandy loam. As this graph shows, permeability is directly related to moisture, and zero permeability or complete restriction of gaseous diffusion through this soil is attained at a moisture content of about 19 per cent. These findings explain why a shallow layer of moist soil, such as results from rain or sprinkling, will restrict loss of vapor from the soil surface. They also explain the ineffectiveness of attempts to kill weeds with carbon disulfide in waterlogged soils.

Soil Type.—Among the characteristics involved in the soil type are the following: nature of parent rocks; processes of soil formation; extent and nature

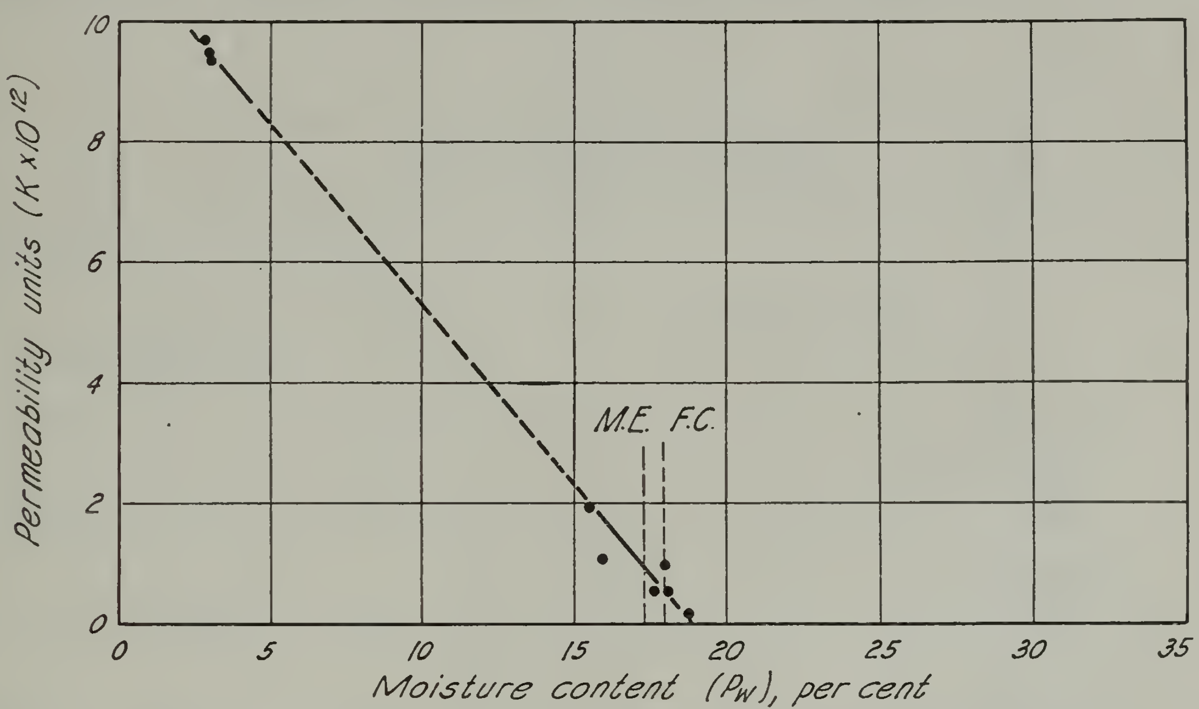

Fig. 6.—Influence of soil moisture content on the permeability of the soil for carbon disulfide vapor in Yolo fine sandy loam, calculated to an apparent density of 1.258 grams per cubic centimeter. (From *Hilgardia* vol. 14, no. 2.)

of the soil profile; particle size distribution (textural grade); and organic-matter content. Intimately concerned with these and often controlled by them are moisture-retaining properties, colloid content, soil color, and soil structure. Closely related to all these characters are the properties of soil biology and, in turn, soil fertility, which are more difficult to define.

Because of the complexity of soil types, any attempt at correlation between them and carbon disulfide toxicity is difficult. By reducing the number of variable factors to a minimum, however, and controlling temperature, compaction, and moisture, it has been possible to extend somewhat the knowledge of carbon disulfide behavior in soils. In order to broaden the scope of application of the studies, soil types representative of important soil groups and agricultural areas were selected.

Texture.—Using the methods of soil preparation described, samples of Yolo fine sandy loam, Yolo loam, and Yolo clay were prepared to an apparent density of approximately 1.20 grams per ml, their air-dry moisture contents being 3.1, 3.6, and 5.8 per cent, respectively. Table 3 gives the permeabilities of these samples, both when air-dry and when moistened to approximately field capacity.

Similar determinations on two Salinas soil samples and two Hanford soils are also presented.

According to these results on pulverized soils, texture affects permeability, the fine-textured soils having relatively low values. This situation may be expected from the particle size distribution in such soils, the clays having chiefly small particles, the loams and sands coarser grains.

The Yolo and Hanford series represent two important groups showing contrasting permeabilities. The former shows relatively high permeability in the dry condition and low in the moist. Hanford has some of the lowest values in the dry condition, and high permeability when moist. These results

TABLE 3

INFLUENCE OF SOIL TEXTURE UPON PERMEABILITY OF THE SOIL TO CARBON DISULFIDE VAPOR

Soil series and texture	Permeability units*	
	Dry (air-dry)	Wet (approximate field capacity)
	$K \times 10^{12}$	$K \times 10^{12}$
Yolo series:		
Fine sandy loam	9.70	1.20
Loam	8.10	1.10
Clay	6.70	0.80
Salinas series:		
Fine sandy loam	8.40	1.89
Clay	6.95	1.51
Hanford series:		
Fine sandy loam	7.60	3.75
Loam	7.40	2.78

* Permeability units are defined by Hagan as "the gram-poises per cm² per second per millimeter of mercury difference in partial pressure per cm."

in the dry soils may possibly be explained by differences in particle shape and size distribution. In the wet condition the character of the colloids is probably the predominating factor in determining permeability.

Soil Series.—Hannesson (1945) has presented data on permeability of surface soils of 6 series, representing 3 different textural grades (table 4).

These data show, again, that the coarse-textured soils have the higher permeability and that permeability is much reduced by the addition of moisture. Among the various soils within a given texture, the differences are not great, but certain soils stand out. Among the clays the Stockton has a low permeability, correlated possibly with the very high colloid content.

Compaction.—The degree of compaction of a soil (that is, its density) determines the size and number of the minute passageways between the soil particles.

When force is applied to a dry soil at right angles to the soil surface, the particles are pressed together with a minimum of disturbance of their spatial relations. Figure 7 illustrates how such compaction affects three Yolo soils. These curves show, as stated above, that textural grade affects permeability,

the coarser textures being the more permeable. They show, further, that permeability decreases with increasing compaction and that, in these three textures within a single series, the three curves appear to diverge from a common point on the base line. Apparently, therefore, if these three soils could be compacted to an apparent density of about 2.0 grams per ml, they would all be impervious to carbon disulfide vapor.

TABLE 4

PERMEABILITY OF SOILS OF SIX SOIL SERIES AND THREE TEXTURES TO CARBON DISULFIDE VAPOR AT TWO MOISTURE CONTENTS

Soil texture and series	Dry soil		Moist soil	
	Moisture content	Permeability units*	Moisture content	Permeability units*
	per cent	*K* × 10^{12}	*per cent*	*K* × 10^{12}
Fine sandy loam:				
Yolo	3.10	8.22	19.9	0.23
	3.00	8.23	18.8	0.70
Salinas	3.10	8.42	16.9	1.89
Hanford	1.70	7.58	17.0	3.75
Loam:				
Egbert	7.70	7.90	32.2	2.25
Yolo	3.45	7.94	22.0	1.60
	3.90	8.19	22.6	0.64
	4.20	7.73	22.4	0.74
Fresno	3.20	8.43	15.9	2.18
	3.20	8.28	....	....
Hanford	3.60	7.30	18.5	2.78
	3.60	7.50	....	....
Clay:				
Salinas	8.90	6.95	30.5	1.51
Yolo	6.10	7.11	31.3	0.67
	6.10	7.26	32.3	0.31
	....	....	31.4	0.90
Stockton	7.10	5.60	27.1	0.60

* Permeability units are defined by Hagan as "the gram-poises per cm^2 per second per millimeter of mercury difference in partial pressure per cm."

According to Hagan (1941) an average value for Yolo soils in the field is 1.32 grams per ml. In dense plow soles, however, apparent-density values may be as high as 1.63 grams per ml in Yolo soils, and higher in others.[12] Where soils are subject to heavy compaction when wet, as on roadways and corrals or in the thin, slick layers beneath a dull plowshare, values of 2.0 grams per ml or more may be obtained (Shaw and Bodman, 1928).

The parent rocks that enter into the composition of most of these soils have an approximate density of 2.65 grams per ml. If the soils could be sufficiently

[12] Bodman, G. B., and N. E. Edlefson. Soil permeability to water. California Agr. Exp. Sta. Project 968:43. 1934. (Unpublished manuscript.)

compacted so that no pore space was left, they would approach this value. Since they become impervious to carbon disulfide vapor at a density of about 2.0, apparently many of the pores in the soil are blind or noncontinuous and do not permit ready diffusion of gases.

Supplementing these studies, Hannesson (1945) tried the effects of compaction on moist soils, applying his forces both at right angles to the surface

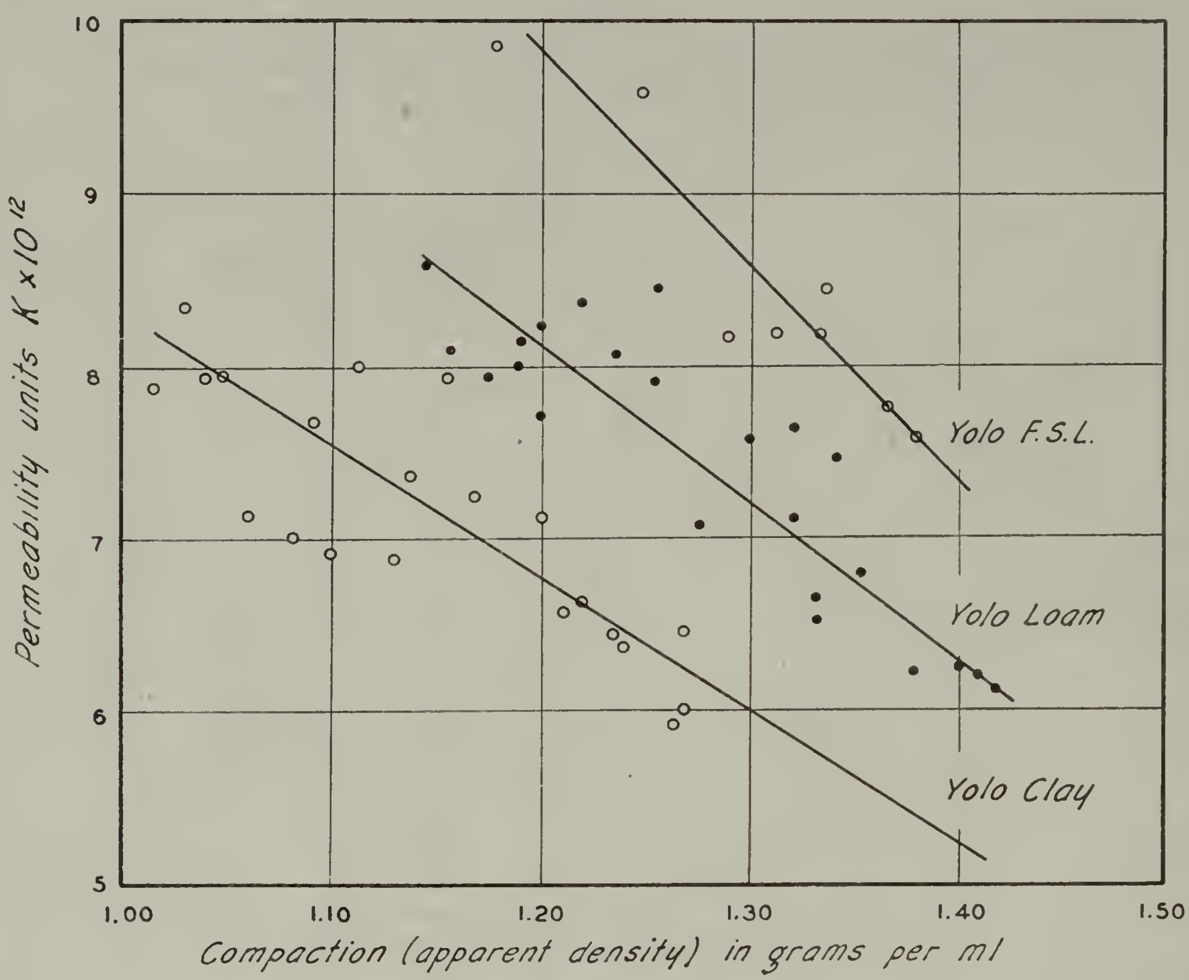

Fig. 7.—Effect of compaction (apparent density) on permeability of air-dry soils to carbon disulfide. Curves were drawn in by approximation. Density values are grams per ml. Moisture contents of these samples are comparable with those reported in table 3. (From *Hilgardia* vol. 16, no. 10.)

(compression) and parallel to the surface (shearing), thus imitating somewhat the effects of certain cultivation implements. Below are given the values that he obtained.

Dominant compaction force	Permeability when air-dry (moisture content about 2 per cent), $K \times 10^{12}$	Permeability when moist (moisture content about 12 per cent), $K \times 10^{12}$
Compression	7.50	1.70
Shearing	0.95	0.15

According to these results, a shearing force is much more effective in compacting a soil than a strictly compressional force. This fact should be apparent from the way in which such forces are applied. A compressional force, when applied, acts to bring the particles closer together with a minimum disturbance of their spatial relations. A shearing force, on the other hand, shifts the soil particles into a more stable configuration in which voids are largely eliminated. The slicking action resulting from plowing or otherwise manipulating the soil while in a wet condition consists of both of these types of compac-

tion. A practical example is the pulling of a plow. If the shares are dull and the soil very moist, both soil layers separated by the plowshare are highly compacted; the result is almost complete loss of permeability to gas. This slicking

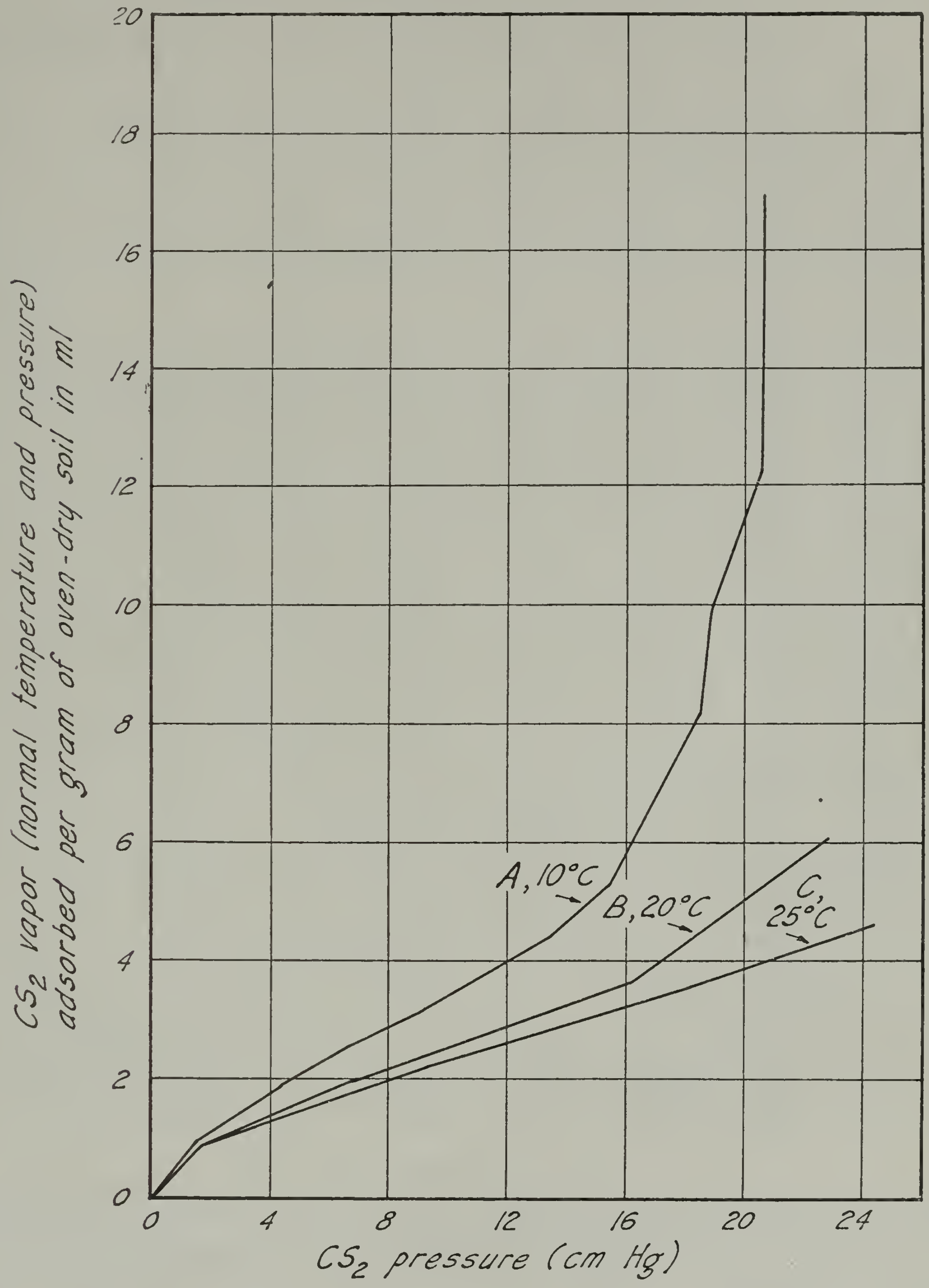

Fig. 8.—Adsorption of carbon disulfide by oven-dry Yolo fine sandy loam at three temperatures (10° C, 20° C, and 25° C). Adsorption is expressed in milliliters of carbon disulfide vapor at standard temperature (0° C) and pressure (1 atmosphere) taken up per gram of oven-dry soil. Pressure is expressed in centimeters of mercury (cm Hg).

action at the bottom of the plow furrow may initiate plow-sole formation. It may also immediately render the subsoil inaccessible to carbon disulfide vapors from liquid placed above it. Thus, although virgin soils are usually

highly pervious, tilled soils may be relatively impervious to gases as a result of various tillage operations to which they have been subjected.

Adsorption.—Because soils contain colloids they tend to adsorb gases and this adsorption process affects any carbon disulfide injected for herbicidal

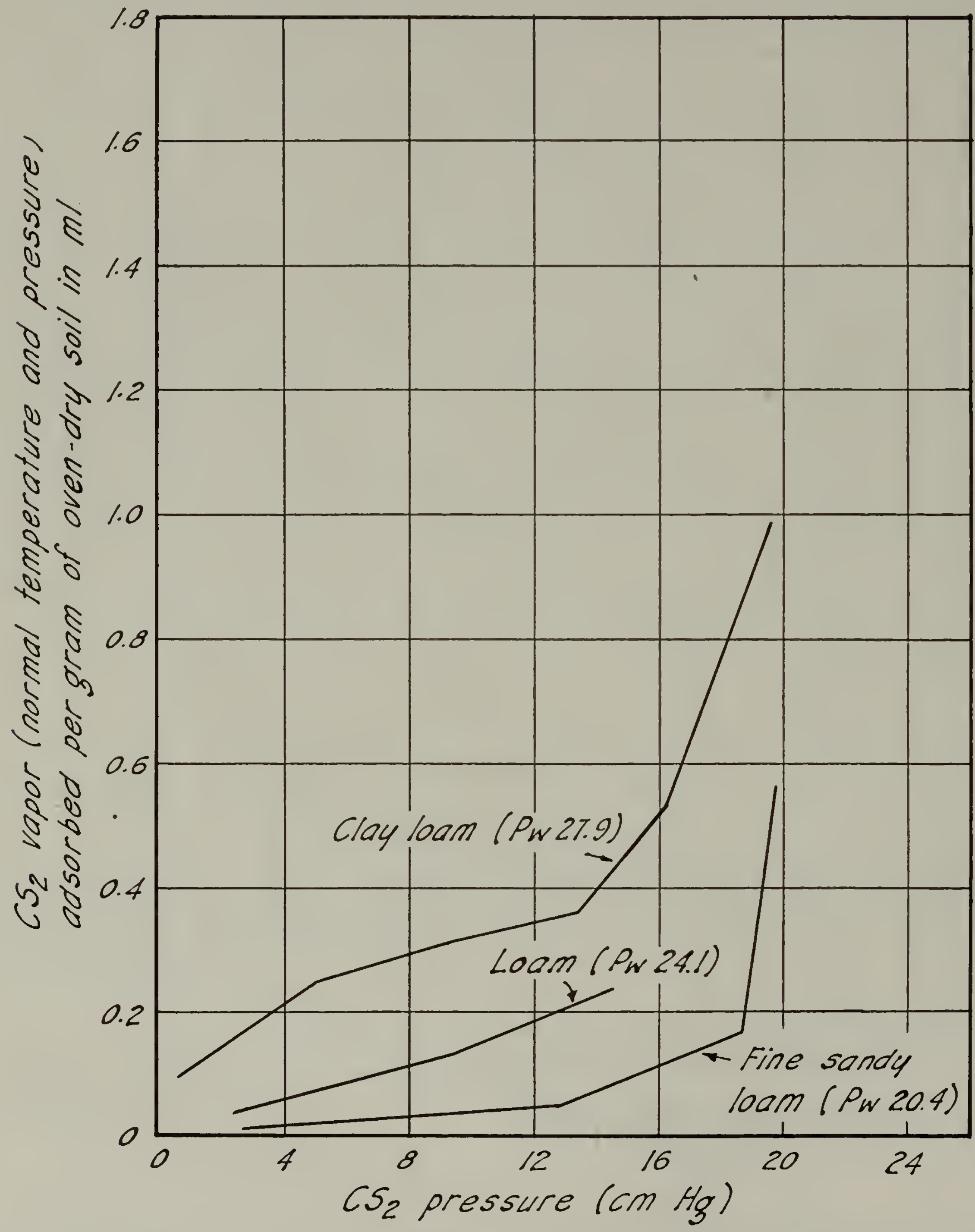

Fig. 9.—Adsorption of carbon disulfide by three textures of Yolo soil. The experiments were performed on soils moistened to field capacity. Adsorption is expressed in milliliters of carbon disulfide vapor at standard temperature and pressure taken up per gram of soil on the oven-dry basis.

purposes. Studies of the effects of temperature, pressure, soil moisture, and texture on carbon disulfide adsorption in a number of soils have been made.

Surface soils of the Yolo series were used in the experiments. For each determination 4 kilograms of soil was placed in a carboy, the carboy was evacuated to a predetermined pressure, and liquid carbon disulfide measured into the carboy. As the carbon disulfide vaporized the pressure increased, finally

reaching approximately that of the outside atmosphere as determined by a mercury manometer in the cork closing the carboy. The total quantity of carbon disulfide added minus the equilibrium amount held in the atmosphere of the carboy was taken as the amount adsorbed. The final concentration in the system was determined by the initial pressure established in the carboy by evacuation.

Curve *A* of figure 8 shows the effect of pressure upon carbon disulfide adsorption by Yolo fine sandy loam at 10° C. Up to a pressure equivalent to about 10 cm of mercury the curve shows a typical adsorption equilibrium, the amount taken up decreasing at higher concentrations (pressures). The curve then inflects, turning rapidly upward. This probably represents capillary condensation of the carbon disulfide in the intermicellar pore spaces of the soil colloids.

Curves *B* and *C* show adsorption at 20° C and 25° C respectively. Less carbon disulfide is adsorbed as the temperature is increased. This is an important relation, for it indicates that at high soil temperatures the carbon disulfide molecules will remain more free in the soil atmosphere and exert a maximum killing effect. Figure 9 shows the relation of soil texture to carbon disulfide adsorption. The fine-textured soil (Yolo clay loam) took up more of the vapor than did the coarse one. Experiments with even finer-textured soils show greater uptake. It should be noted that the soils used in the experiments reported in figure 9 were moist and that the vertical scale has been much expanded to show detail in the low absorption region. The effect of soil texture is reflected in field practice where higher dosages are more often required in heavy clay soils than in light sandy ones.

In figure 10 the vertical scale has been somewhat contracted but it is still five times that of figure 8. This has been set to steepen the curve for oven-dry Yolo fine sandy loam in order that the curves for moist soils can be included. Curve *A* shows adsorption by oven-dry soil which takes up large quantities of carbon disulfide vapor at relatively low concentrations. The pore spaces in this soil are unoccupied by water and have a maximum capacity for adsorption. At 8.4 per cent moisture content (curve *B*), or about the permanent wilting percentage, for this soil much less vapor is absorbed at the low concentrations, and only when carbon disulfide vapor pressures of 14 to 18 cm of mercury are reached does the soil start to adsorb rapidly. Curve *C* showing adsorption at approximately field capacity indicates even lower uptake at the low pressures.

Consideration of these relations brings out a number of points of great importance in the use of carbon disulfide in the field. In the soil the partial pressure of carbon disulfide vapor may reach a value as high as 20 cm of mercury. Assuming an average value of 10 cm throughout the soil at 10° C, when volatilization of the liquid is complete, a Yolo soil of coarse texture may take up around 20 per cent of the carbon disulfide added in a standard application. At the highest summer temperatures somewhat less would be adsorbed. Fine-textured soils would hold more; as high as 75 per cent being indicated by the results in a cool clay soil at the permanent wilting percentage or below. Moisture in the soil tends to lower the soil's capacity to adsorb carbon disulfide but, on the other hand, restricts the ready diffusion of the gas. For this reason

carbon disulfide remains in high concentration in localized regions longer in wet soils than in dry. The fact that successful control of weeds may be had under a fairly wide range of soil moisture conditions indicates that these two

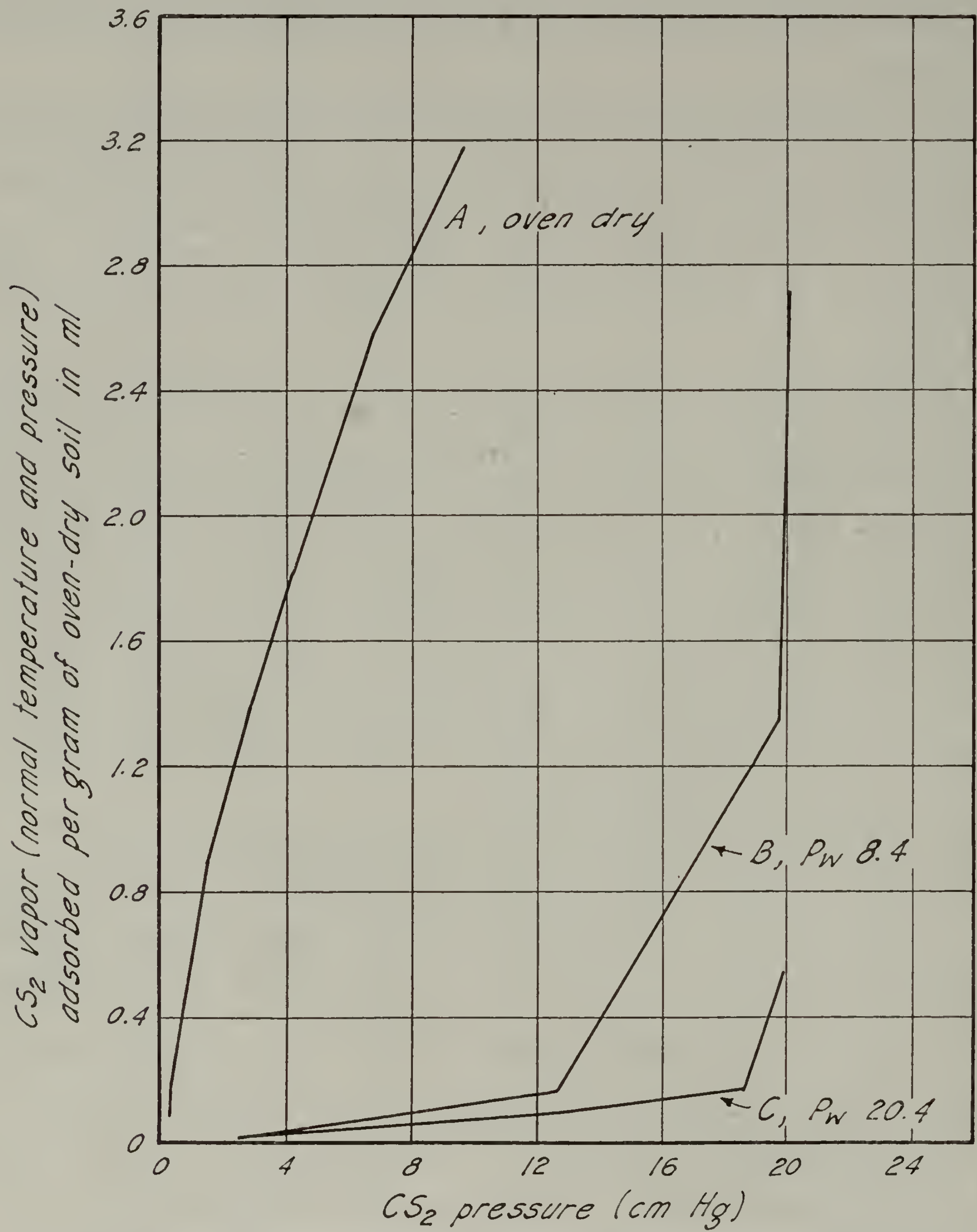

Fig. 10.—Adsorption of carbon disulfide by Yolo fine sandy loam at three moisture contents. Adsorption is expressed in milliliters of carbon disulfide vapor at standard temperature and pressure taken up per gram of soil on the oven-dry basis.

effects tend to compensate each other and make soil moisture less important than some other factors in weed control.

On the other hand, high soil temperatures tend to lower the adsorptive capacity of the soil and at the same time speed up diffusion. While both of these tend to stimulate surface losses from the soil, if the surface is properly sealed they cause high toxicity and effective results. Soil texture is also important and must be taken into account because the effects upon adsorption and diffusion are cumulative as in the case of temperature. Fine-textured soils

tend to adsorb much carbon disulfide; they also hinder diffusion if structure is not well developed. One would expect from this that coarse soils might be successfully treated at almost any time; fine-textured soils of low permeability should be treated during summer. Field experience would seem to bear out this deduction. Cold clay soils offer the greatest obstacles to successful treatment with carbon disulfide, and this is particularly true when they are excessively moist and lacking in structure.

All of the phenomena so far described take place in laboratory samples of soils so prepared that soil structure is largely eliminated as a variable. In the field, structural characteristics are very pronounced and may in many instances overshadow the factors so far discussed. In the following section studies involving structure will be described.

PERMEABILITY STUDIES ON FIELD CORES

Since soil columns used in the studies just described were prepared from dried pulverized soil, all characteristics resulting from natural structures or from the activities of earthworms, insects, plant roots, and other organisms were largely obliterated. Mechanical difficulties were encountered in determining carbon disulfide diffusion through field cores, because of a lack of suitable impermeable materials for preventing leakage of this gas along the cylinder walls.

Buehrer's (1932) method of characterizing soil structure by low-pressure air flow was adapted to the study of permeability in field cores by the use of a rubber-lined sleeve[13] to surround the core and hold it in position during measurement.

Preparation of Cores.—The field cores used were taken near plots established to study the effects of soil type, spacing, depth of application, and dosage on the killing of perennial weeds by carbon disulfide. Cores from soils at moisture contents near field capacity were found most suitable, since drier ones crumbled in handling. Accordingly, small plots were irrigated enough to moisten them to 4 feet, and cores were taken 1 week afterward. In winter, plots were sampled directly, since they were already near field capacity.

Cores were taken with a cylindrical cutter, about 4 inches in diameter, forced into the soil by an anchored jackscrew. They were removed in successive segments either 4 or 6 inches long, placed intact into metal cans, sealed, and transported to the laboratory. Smaller cores, 4.7 cm in diameter and 5.0 cm in length, were taken from the field cores for determination of permeability. Natural structure was maintained by carefully paring the outer soil away with a sharp knife in advance of the leading edge of the cylindrical core cutter. To avoid slicking of the end surfaces, the knife was held at a high angle in trimming the cores to length. Moisture was determined on the soil trimmed from the large cores in reducing them to the final diameter.

Determination of Apparent Density.—Each small core was next placed in a cylindrical metal sleeve 5.0 cm in diameter and 5.2 cm in length, lined with a thin rubber tube cemented to the sleeve at the ends. The rubber liner (prepared from dental dam material) was held in close contact with the soil core

[13] Originally devised by Ross E. Moore, formerly Instructor in Soil Technology and Junior Soil Technologist in the Experiment Station.

by water introduced between the sleeve and the liner through a side tube in the sleeve. A head of 50.0 cm of water pressure was used to press the liner around the core.

To give the volume of the core, the volume of water and the unoccupied volume at the ends of the core were measured and subtracted from the total volume of the sleeve. Because it accounts for surface irregularities, this method provides a satisfactory measure of core volume.

Each core was immediately weighed; and from volume and weight, corrected to the air-dry basis, the apparent density was computed. This gives a measure of relative compaction at various depths, provided the texture is uniform within the depth sampled.

Measurement of Air Flow.—With the core in place within the rubber liner of the metal sleeve, the sleeve was clamped between two end plates, each provided with an exit tube. Rubber gaskets between the sleeve and plates prevented the air from entering or escaping except through the tubes. One tube was then connected to a source of constant air pressure equivalent to 5 mm of 95 per cent ethyl alcohol. The volume of air moving through in unit time was measured.

Calculation of Resistance Factor.—The rate of air flow through the soil column, in cubic centimeters per second, was used in computing the resistance factor. Free flow through the unoccupied apparatus was 6.7 ml per second. Using this as zero resistance, and no flow as 100 per cent resistance, the factor was calculated as follows: Taking a measured flow of 3.0 ml per second, the factor would be $\frac{6.7 - 3.0}{6.7} \times 100 = 44.8$ per cent. Because resistance parallels compaction in a general way, air flows were computed to resistance, thus making comparisons more graphic.

The figures that follow show the resistances, apparent densities, and moisture contents of the successive fractions of soil profiles studied. The values are usually averages of two samples. Those for the three Yolo soils from Davis are based on three samples. Where resistances at field capacity and in the air-dry condition are compared, cores from only one of the duplicate samplings were measured in the air-dry condition. Depths plotted in the graphs are distances at which the median points of the cores lie below the soil surface.

Interpretation of Air-Flow Data.—The Yolo series of soils was studied in greater detail than any other. Figure 11 illustrates the results obtained on a Yolo loam. The curves are the average of three runs. Curve *R* records the resistance of the cores to air flow; *C* is the compaction or apparent density; and *Pw* is the moisture content. The scale at the left is percentage and is used in reading both resistance and moisture content. The scale at the right is density in grams per ml and has been arbitrarily adjusted to make curves *R* and *C* coincide in range. It must be noted that this scale is different in different figures.

Since most of the soils studied gave results that fall in a general pattern not essentially different from that of Yolo loam, these curves (fig. 11) will be discussed in detail. Starting in the topsoil, resistance is high in the first core, probably because of compaction by the beating rain. The compaction curve shows this to be the soil fraction with the highest density. Resistance and

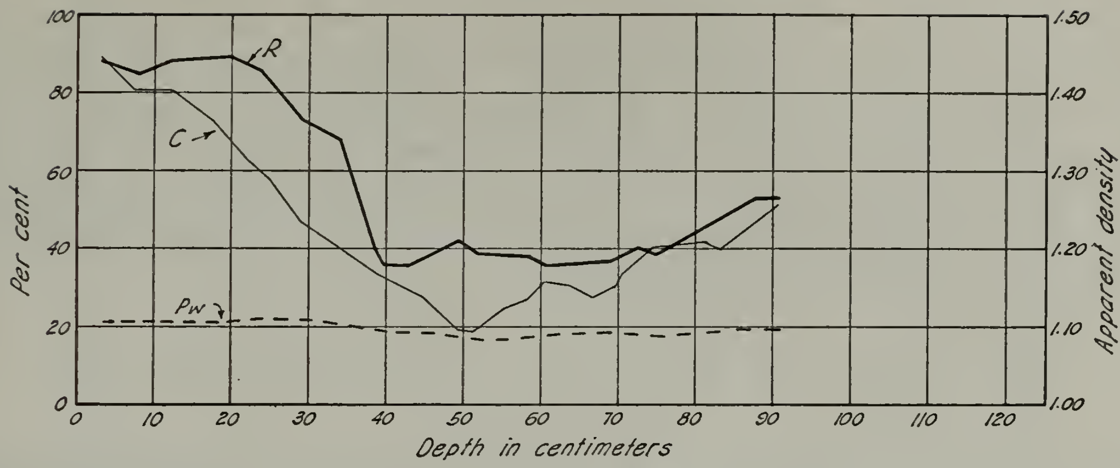

Fig. 11.—Changes in resistance to air flow (R), in compaction (C), and in moisture content (Pw) with depth in Yolo loam. All values are averages of measurements on three separate columns. Resistance is expressed in percentage and is read on the left-hand scale. Compaction is expressed as apparent density, in grams per ml, on the right-hand scale.

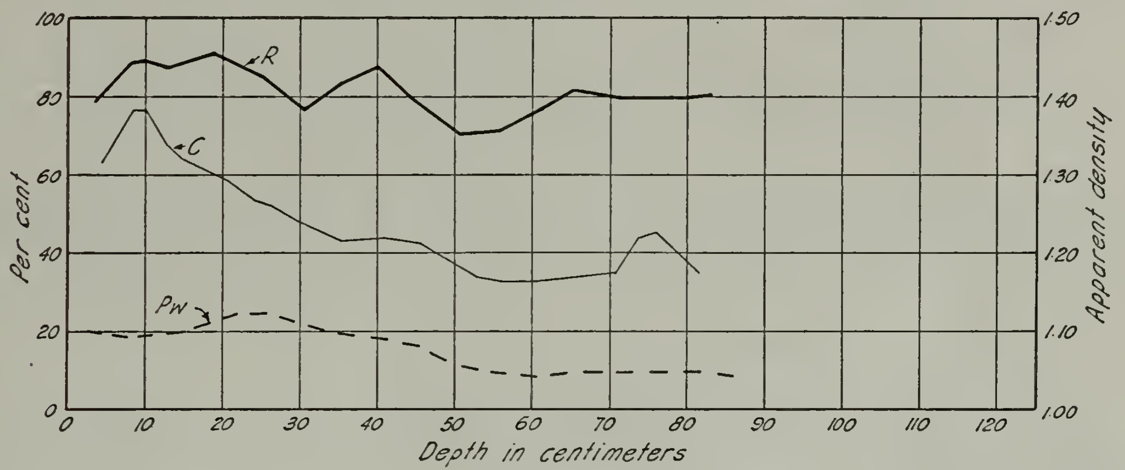

Fig. 12.—Changes in resistance to air flow (R), in compaction (C), and in moisture content (Pw) with depth in Yolo fine sandy loam. Average of four columns.

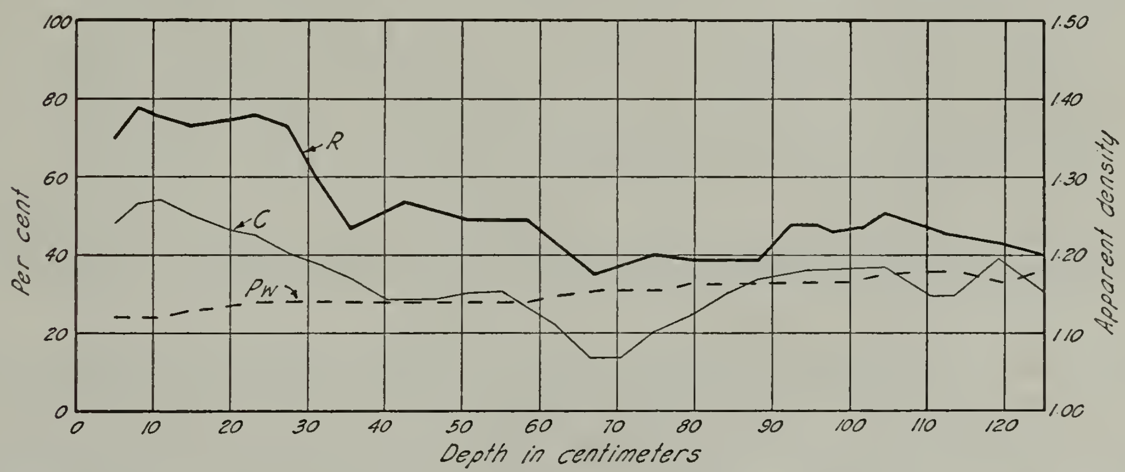

Fig. 13.—Changes in resistance to air flow (R), in compaction (C), and in moisture content (Pw) with depth in Yolo clay loam. Average of four columns.

compaction both drop in the second soil core, where the structure is somewhat looser and considerable straw and trash have been incorporated by previous plowing. Resistance then goes through a maximum in the next three cores, representing soil in the 6- to 10-inch (15- to 25-cm) horizon. This, the plow-sole region, is characterized by thin layers of slick or highly compacted soil formed by mechanical action of the plowshare. Since the compaction falls

through this region, evidently the impervious regions are of limited extent and do not occupy the complete soil mass. At a depth of about 10 inches (25 cm) the resistance starts down. It decreases rapidly to 16 inches (40 cm) and then levels off with little change, until from 30 inches (75 cm) downward it increases slightly again. Compaction likewise drops through the 10- to 20-inch (25- to 50-cm) layers, where it reverses and rises steadily to a value of 1.25 grams per ml at 36 inches (92 cm).

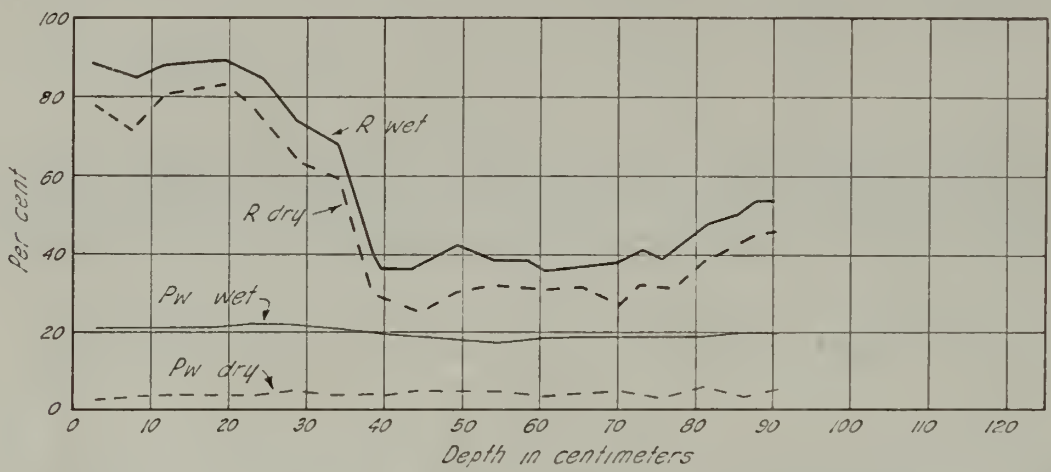

Fig. 14.—Changes in resistance to air flow in Yolo loam at field capacity (*R*-wet) and air-dry (*R*-dry), and in moisture content (*Pw*-wet, *Pw*-dry) with depth. Average of three columns.

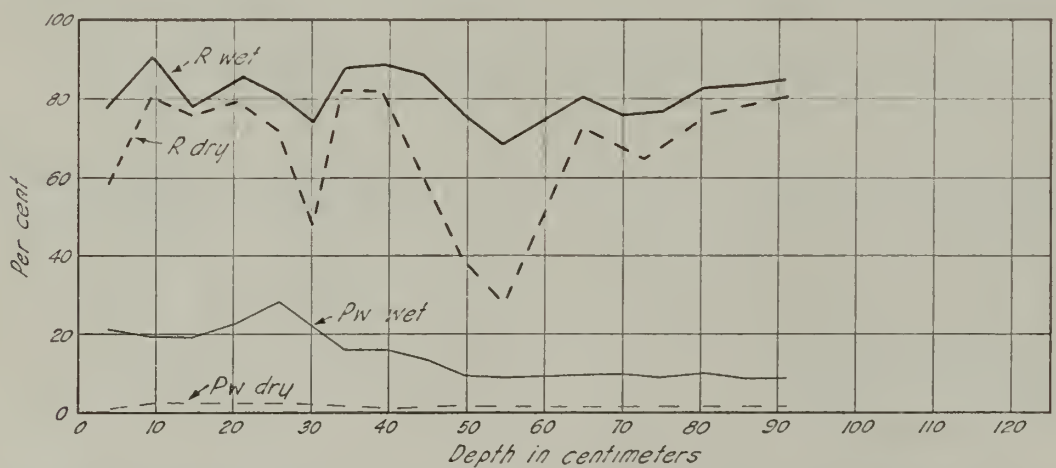

Fig. 15.—Changes in resistance to air flow, and in moisture content with depth, in Yolo fine sandy loam at two moisture contents (field capacity and air-dry). One column.

The region of maximum decrease in resistance is that in which biological activities are important and where cultural practices have little effect on structure. In this region usually occurs a large proportion of the storage-root system of perennial weeds; and here gaseous diffusion becomes increasingly free as the fumigant vapor moves downward and spreads through the soil.

The small increase in resistance below 30 inches (75 cm) may represent a change in texture, or it may reflect reduced biological activity and a denser structure. These are encountered in Yolo soils. Figures 12 and 13 present similar studies on two additional Yolo soils.

Effect of Soil Moisture on Resistance.—Resistances of all field cores were measured at approximately their field capacity. A notable feature is the large change in permeability, with little variation in moisture, in different sections

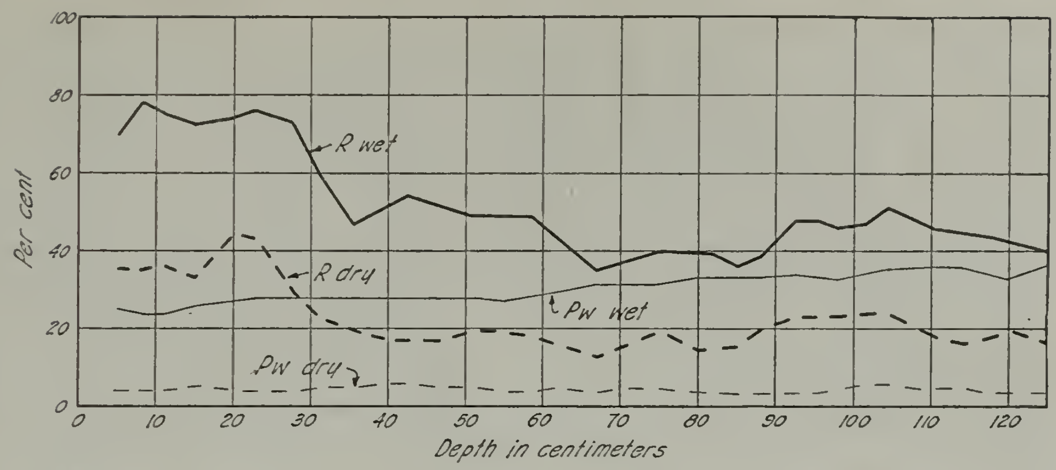

Fig. 16.—Changes in resistance to air flow, and in moisture content with depth, in Yolo clay loam at two moisture contents (field capacity and air-dry). Average of three columns.

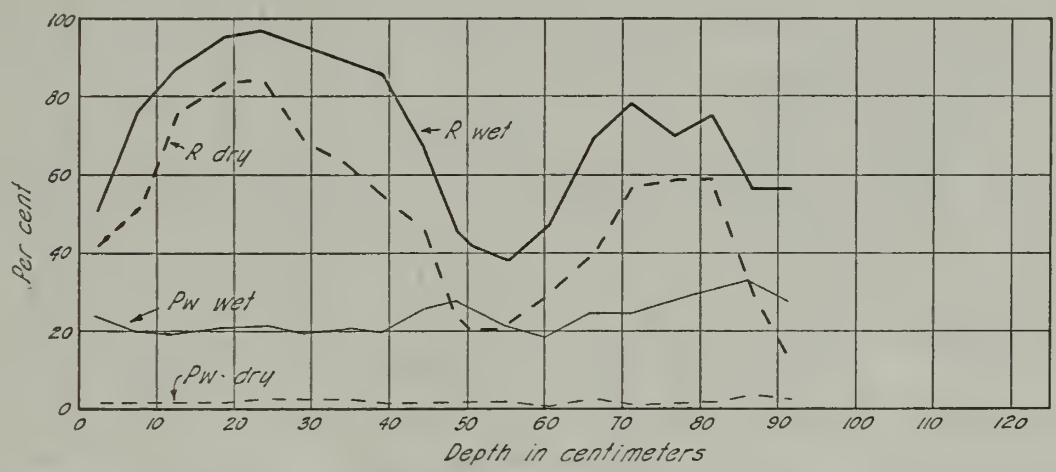

Fig. 17.—Changes in resistance to air flow, and in moisture content with depth, in Yolo silt loam at two moisture contents (field capacity and air-dry). Average of two columns.

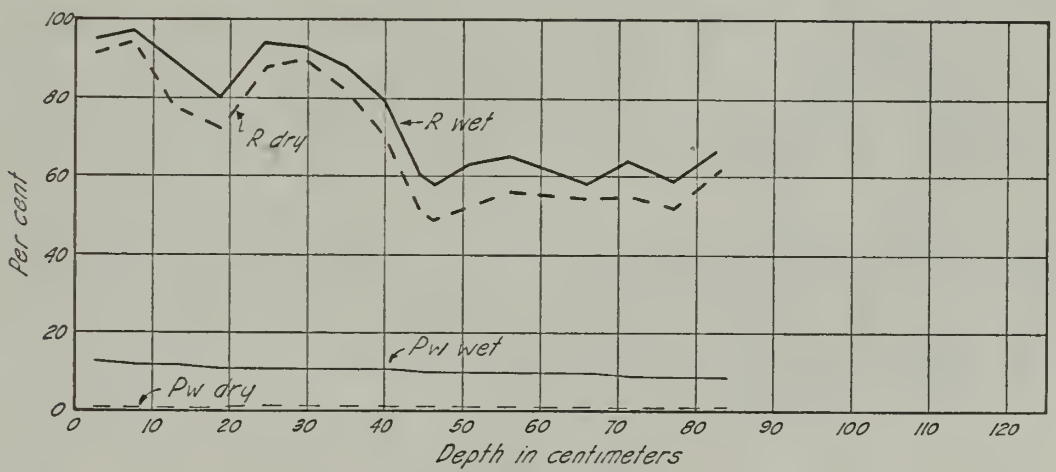

Fig. 18.—Changes in resistance to air flow, and in moisture content with depth, in Dinuba sandy loam at two moisture contents (field capacity and air-dry). Average of two columns.

of a single profile. The laboratory studies (pp. 11 to 23) had shown that soil moisture, by occupying the voids between the soil particles, and by hydrating the colloids, had reduced permeability to almost zero at field capacity. The effect of moisture on the permeability of field cores had, therefore, to be evaluated.

Several sets of cores were allowed to stand on the laboratory table until

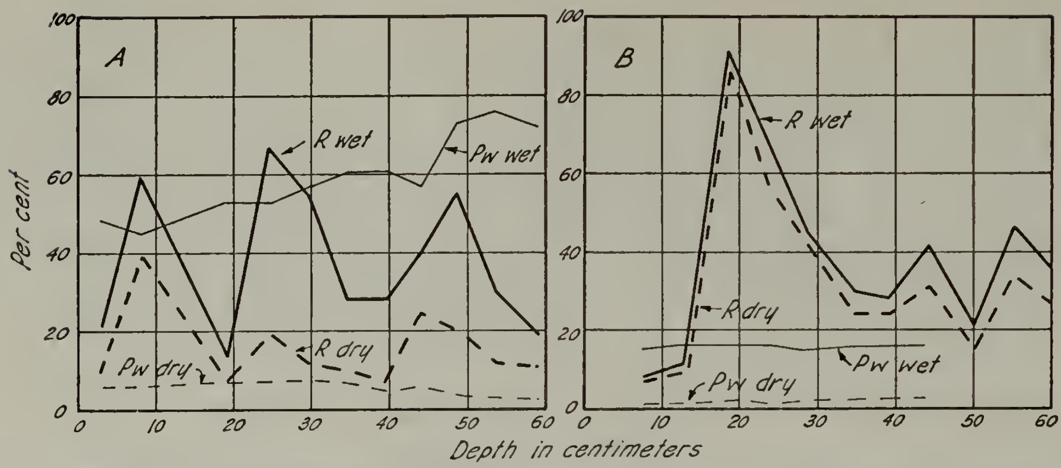

Fig. 19.—Changes in resistance to air flow, and in moisture content with depth, in two California soils at two moisture contents: *A*, Gridley loam; *B*, Sacramento clay. A single column was measured for each soil.

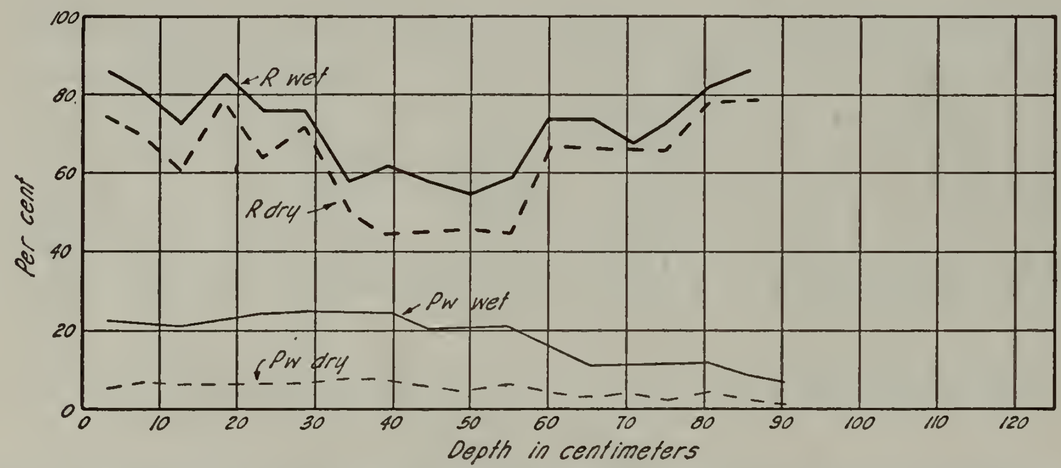

Fig. 20.—Changes in resistance to air flow, and in moisture content with depth, in Hanford fine sandy loam at two moisture contents (field capacity and air-dry). Average of two columns.

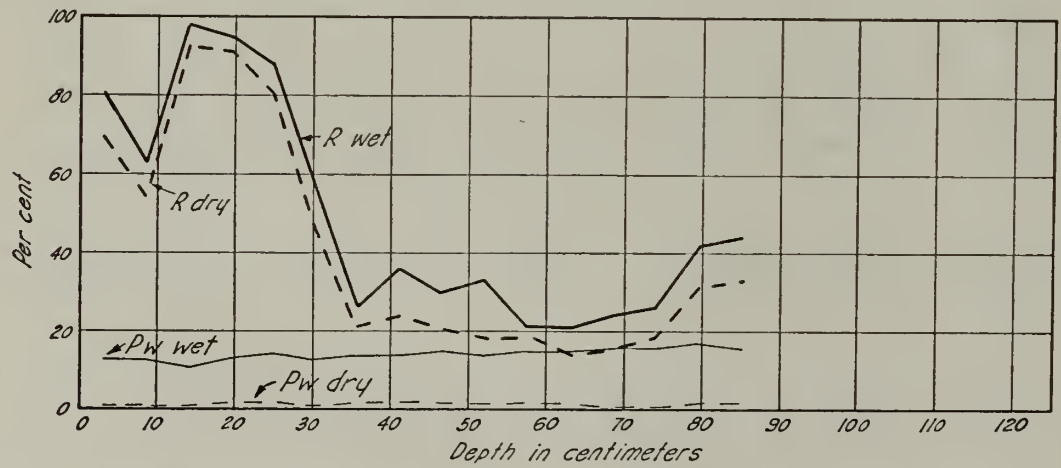

Fig. 21.—Changes in resistance to air flow, and in moisture content with depth, in Honcut loam at two moisture contents (field capacity and air-dry). One column.

air-dry. An attempt was also made to obtain moisture contents between the air-dry condition and field capacity by exposing cores to known concentrations of sulfuric acid in desiccators. Since fluctuations in moisture within the range encountered in the field prove less important than might be expected from studies on artificially packed samples, work on intermediate moisture contents was limited.

Figures 14 to 21 give the results of the moisture studies. Although lowering the moisture content increases permeability, the percentage of increase is usually less than the variations normally existing in different cores from a profile. Absolute increases in permeability from drying are greatest in soils already rather permeable when wet. Relative increase in permeability is greatest in impervious regions such as plow sole. Highly impermeable layers may not become permeable upon drying, but permeable layers may become even more permeable upon drying.

Summarization of Air-Flow Data.—Detailed interpretations of air-flow data on other soil types are presented in the section that follows (pp. 29 to 44), where results of plot tests are correlated. From study of many profiles, representing a variety of soils, conclusions may be summarized in the following statements: (1) In general field cores of the finer-textured soil types are more permeable than those of the coarser soil types, at least below plow depth. This is at variance with results obtained upon laboratory-packed soils and indicates that a high colloid content is conducive to permeable soil structure. In the absence of well-developed structure, cores of coarser-textured soils are more permeable. (2) Within a given profile, permeability is usually correlated with apparent density. Exceptions usually involve dense or slick layers of limited thickness. (3) Plow sole was characteristic of most soils sampled, and the plow sole was the least permeable portion of the profile. A few soils not recently cultivated had denser surface layers. These samples usually came from pastured fields where the surface was packed.

Judging from these results, structure as determined by the sum total of natural agencies, such as rodents, earthworms, plant roots, insects, fungi, bacteria, and colloidal hydration, becomes dominant in determining the permeability of soils as they occur in the field. Soil layers below the reach of tillage implements are permeable to gas unless they contain dense alluvial strata, claypan,[14] hardpan, or standing water. Within the tilled portion, plow sole[15] usually constitutes a relatively impervious layer which, because of its high resistance, may have its permeability increased twofold or more by drying. This moisture relation is important where treatment with carbon disulfide must be made through such a plow sole.

Moisture is also of primary importance in surface sealing. Where, because of high water-table conditions or frequent irrigation practice, perennial weeds have feeder roots within 6 inches of the soil surface, shallow injection followed by sprinkling, or injection performed immediately after rainfall, may be resorted to.

AIR-FLOW AND PLOT STUDIES ON SEVERAL CALIFORNIA SOILS

To define more accurately the volume and spacing of carbon disulfide injections, plots involving several conditions of soil moisture and temperature were established at Davis. Midsummer treatments on dry soils were also made in several other localities, including those from which samples for air-flow measurement had been taken.

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[14] The term *claypan* as used here refers to a dense, highly colloidal layer in the soil whereas *hardpan* represents a cemented impervious layer. Both occur below the soil surface at varying depths and are formed by natural agencies during the development of the soil.

[15] *Plow sole* is a relatively impermeable layer resulting from plowing or other tillage operations and is usually present within the limits of the 4- to 12-inch depths.

TABLE 5

SPACINGS BETWEEN INJECTION POINTS AND VOLUME OF LIQUID PER INJECTION TO GIVE INDICATED NUMBERS OF POINTS AND POUNDS OF CARBON DISULFIDE PER SQUARE-ROD PLOT

Injection points	Spacing		Pounds of carbon disulfide per square rod				
	Between rows	In rows	5	10	15	20	25
			Volume of liquid per injection				
number	*inches*	*inches*	*ml*	*ml*	*ml*	*ml*	*ml*
30	33.6	38.8	60	120	180	240	300
60	23.8	27.5	30	60	90	120	150
90	19.3	22.3	20	40	60	80	100
120	16.8	19.4	15	30	45	60	75
150	15.0	17.3	12	24	36	48	60

TABLE 6

EFFECT OF DOSAGE, SPACING, AND DEPTH OF INJECTION OF CARBON DISULFIDE (ANCHOR BRAND*) AT DIFFERENT SOIL MOISTURE CONTENTS ON WILD MORNING-GLORY IN YOLO LOAM
(Plots Treated August 8 to September 28, 1940)

Depth, and pounds per square rod	Holes per square rod	Dosage per hole	Percentage kill	
			Dry soil (at permanent wilting percentage)	Moist soil (recently irrigated)
	number	*ml*	*per cent*	*per cent*
6 inches:				
5	90	20	72	45
5	60	30	35	72
5	30	60	64	37
10	90	40	87	97
10	60	60	92	95
10	30	120	93	97
15	90	60	100	98
15	60	90	96	97
15	30	180	100	83
10 inches:				
5	90	20	78	91
5	60	30	45	40
5	30	60	68	55
10	90	40	97	95
10	60	60	97	58
10	30	120	99	61
15	90	60	100	94
15	60	90	96	54
15	30	180	100	92

* For description of brands of carbon disulfide see footnote 2, page 3.

TABLE 7

EFFECT OF DOSAGE, SPACING, AND DEPTH OF INJECTION OF CARBON DISULFIDE AT DIFFERENT SOIL MOISTURES AND SOIL TEMPERATURES (AS DETERMINED BY SEASON) ON WILD MORNING-GLORY IN YOLO LOAM

Date of treatment and soil moisture	Method of treatment				Percentage kill	
	Amount per square rod	Holes per square rod	Dosage per hole	Depth	Anchor Brand	Activated
	pounds	*number*	*ml*	*inches*	*per cent*	*per cent*
Feb. 27, 1941, soil at field capacity..	20.0	90	80.0	6	80	..
	20.0	120	60.0	6	60	..
	20.0	150	48.0	6	98	..
	25.0	90	100.0	6	90	93
	25.0	120	75.0	6	80	93
	25.0	150	60.0	6	100	97
June 11, 1941, soil at field capacity..	15.0	30	180.0	6	94	..
	15.0	60	90.0	6	99	..
	15.0	90	60.0	6	99	99
	20.0	30	240.0	6	94	96
	20.0	60	120.0	6	100	100
	20.0	120	60.0	6	100	..
Aug. 5, 1941, soil dry..............	10.0	30	120.0	6	94	87
	10.0	120	30.0	6	96	87
	12.5	30	150.0	6	97	96
	12.5	120	37.5	6	98	96
	15.0	30	180.0	6	100	..
	15.0	120	45.0	6	97	..
	10.0	30	120.0	10	93	95
	10.0	120	30.0	10	97	97
Aug. 20, 1941, soil at field capacity..	15.0	60	90.0	6	90	..
	15.0	90	60.0	6	98	..
	15.0	120	45.0	6	94	87
	20.0	60	120.0	6	99	80
	20.0	120	60.0	6	100	98
	22.5	90	90.0	6	98	..
Sept. 29, and Oct. 6, 1941, soil dry, windy weather.............	15.0	30	180.0	6	75	..
	15.0	120	45.0	6	90	90
	20.0	30	240.0	6	95	..
	20.0	120	60.0	6	97	95
	25.0	30	300.0	6	90	..
	25.0	120	75.0	6	99	98
Sept. 22 and Oct. 2, 1941, soil dry, still weather................	15.0	30	180.0	6	80	..
	15.0	120	45.0	6	90	75
	20.0	30	240.0	6	85	..
	20.0	120	60.0	6	95	95
	25.0	30	300.0	6	90	..
	25.0	120	75.0	6	98	95
Nov. 11, 1941, top 6 inches wet, dry below.......................	15.0	120	45.0	6	99	..
	20.0	30	240.0	6	99	..
	20.0	60	120.0	6	99	..
	20.0	120	60.0	6	100	..
	25.0	120	75.0	6	100	..
	15.0	120	45.0	8	99	99
	20.0	120	60.0	8	100	100
	25.0	60	150.0	8	99	..
	25.0	120	75.0	8	100	100
Jan. 21, 1942, soil at field capacity....	20.0	90	80.0	6	99	..
	20.0	120	60.0	6	100	99
	20.0	150	48.0	6	99	..
	25.0	90	100.0	6	99	99
	25.0	120	75.0	6	99	..
	25.0	150	60.0	6	99	99

In setting up the schedule of treatments, the exact values of the standard dosage, 19.88 pounds per square rod, and the number of injection points per square rod, 121, were for convenience rounded off to 20 pounds and 120 points. A schedule of treatments was then set up on the arbitrarily chosen basis of ¼, ½, ¾, 1, and 1¼ times 20 pounds, and 120 points. Although in

TABLE 8

Effect of Dosage, Spacing, and Depth of Injection of Carbon Disulfide at Different Soil Moistures and Soil Temperatures (as Determined by Season) on Wild Morning-Glory in Yolo Fine Sandy Loam

Date of treatment, and soil moisture	Method of treatment				Percentage kill	
	Amount per square rod	Holes per square rod	Dosage per hole	Depth	Anchor Brand	Activated
	pounds	*number*	*ml*	*inches*	*per cent*	*per cent*
Feb. 17, 1941, soil at field capacity..	20.0	90	80.0	6	99	...
	20.0	120	60.0	6	98	99
	20.0	150	48.0	6	97	..
	25.0	90	100.0	6	99	99
	25.0	120	75.0	6	99	..
	25.0	150	60.0	6	99	99
Aug. 1, 1941, soil dry...............	7.5	30	90.0	6	75	75
	7.5	120	22.5	6	65	25
	10.0	30	120.0	6	90	80
	10.0	120	30.0	6	75	90
	12.5	30	150.0	6	95	..
	12.5	120	37.5	6	95	..
	7.5	30	90.0	10	60	25
	7.5	120	22.5	10	50	30
Nov. 14, 1941, top 12 inches moist, dry below........................	15.0	120	45.0	6	99	..
	20.0	30	240.0	6	99	..
	20.0	60	120.0	6	99	..
	20.0	120	60.0	6	98	..
	15.0	120	45.0	8	99	99
	20.0	120	60.0	8	90	99
Feb. 7 to Feb. 11, 1942, soil at field capacity.....................	20.0	90	80.0	6	99	..
	20.0	120	60.0	6	99	99
	20.0	150	48.0	6	99	..
	25.0	90	100.0	6	100	99
	25.0	120	75.0	6	99	..
	25.0	150	60.0	6	99	100

commercial applications, and in our previous plot-test work also, the spacings between rows are the same as between injection points in the row, the system proposed by Taylor (1939) was adopted as providing for the complete exposure of the soil mass to vapors of a fumigant with the minimum amount of overlap between adjacent diffusion circles. In this system the distance between points in the rows is 1.15 times the distance between rows. Table 5 shows the calculated spacings between points and between rows, and also the milliliters of carbon disulfide liquid per injection to give 5, 10, 15, 20, and 25 pounds per square rod at 30, 60, 90, 120, and 150 injection points.

The most complete series of tests was made on Yolo loam. As figure 11 shows, there was a close correlation between resistance to air flow and apparent

density of the soil, both being high in the top 10 inches (25 cm) and much less below.

The effects of dosage rate, soil moisture, and depth of injection of carbon disulfide on wild morning-glory were tested on plots of Yolo loam in 1940. Table 6 presents the results. Evidently 15.0 pounds was necessary for a practical kill, and certain plots at this rate were not satisfactory. Treatments were somewhat more effective on dry plots than on wet ones. Whereas on the dry plots the 10-inch depth was slightly better than the 6-inch (15 cm), on the wet plots the reverse was true, probably because of crown survival.

In 1941 a more extensive series was used (table 7). Soil moisture and temperature were the main variables in these plots. Anchor Brand and "Activated" carbon disulfide[16] (a product containing compounds to reduce the vapor pressure) were compared. One series was treated in windy weather and one on still days, to determine how moving air affects soil ventilation. Dosage was also varied.

Plots treated on February 27, 1941, were at the minimum seasonal soil temperature. The moisture content was at field capacity. Both 20.0 and 25.0 pounds were effective at 150 injections per square rod.

Plots treated June 11 were at intermediate soil temperature and field capacity. Only the widest spacing (30 holes) reduced effectiveness at this temperature.

Both wet and dry plots were treated during maximum soil temperatures in August. Under these conditions spacing, within the limits tested, had no significant effect. Dosage as low as 10.0 pounds per square rod proved quite successful. Moisture seemed to have no bearing on the results.

Plots treated in windy and still weather in September and October showed no significant differences. This soil had a well-compacted surface and was very permeable below (fig. 11). Under less favorable conditions, wind might have had more influence.

Plots treated November 11, 1941, had 6 inches (15 cm) of moist soil on the surface, with the subsoil less moist. Soil moistures were as follows:

Depth of soil, in inches	Depth of soil, in cm	Soil moisture, per cent
0 to 6	0 to 15	23.0
6 to 12	15 to 30	13.6
12 to 24	30 to 61	13.7
24 to 36	61 to 92	15.5
36 to 48	92 to 122	14.4

With this excellent surface seal in a soil still fairly warm, the toxic vapors were well distributed, and even 15.0 pounds gave good results.

Fine controls were also obtained on January 21, 1942, at minimum seasonal soil temperature and with moisture at field capacity. Throughout the series on Yolo loam, results with Anchor Brand and "Activated" carbon disulfide were not different.

Yolo fine sandy loam was tested by air-flow and plot studies. As shown in figure 12, resistance was fairly high throughout, there being less evidence of plow sole than in most soils tested. This soil is characterized by numerous narrow strata and lenses of dense material. The maintained resistance despite

[16] See footnote 2.

TABLE 9

Effect of Dosage, Spacing, and Depth of Injection of Carbon Disulfide at Different Soil Moistures and Soil Temperatures (as Determined by Season) on Wild Morning-Glory in Yolo Clay Loam

Date of treatment, and soil moisture	Method of treatment: Amount per square rod	Holes per square rod	Dosage per hole	Depth	Percentage kill: Anchor Brand	Activated
	pounds	*number*	*ml*	*inches*	*per cent*	*per cent*
Feb. 25, 1941, soil at field capacity..	20.0	90	80.0	6	97	..
	20.0	120	60.0	6	92	91
	20.0	150	48.0	6	94	..
	25.0	90	100.0	6	98	..
	25.0	120	75.0	6	87	91
	25.0	150	60.0	6	95	95
June 13, 1941, soil at field capacity...	15.0	60	90.0	6	94	..
	15.0	90	60.0	6	97	97
	20.0	30	240.0	6	90	93
	20.0	60	120.0	6	96	..
	20.0	120	60.0	6	96	95
Aug. 6 to Aug. 10, 1941, soil dry and cracked on top, moist below..	10.0	30	120.0	6	50	25
	10.0	120	30.0	6	75	40
	12.5	30	150.0	6	50	85
	12.5	120	37.5	6	50	95
	15.0	30	180.0	6	60	..
	15.0	120	45.0	6	40	..
	10.0	30	120.0	9	25	30
	10.0	120	30.0	9	25	30
Aug. 20, 1941, soil at field capacity..	15.0	60	90.0	6	70	..
	15.0	90	60.0	6	70	..
	15.0	120	45.0	6	80	90
	20.0	60	120.0	6	85	90
	20.0	90	80.0	6	95	..
	20.0	120	60.0	6	90	95
Nov. 13, 1941, top 7 inches moist, less moist below..................	20.0	30	240.0	6	75	..
	20.0	120	60.0	6	98	..
	25.0	120	75.0	6	96	..
	20.0	60	120.0	8	93	..
	20.0	120	60.0	8	97	95
	25.0	60	150.0	8	99	..
	25.0	120	75.0	8	99	99
Jan. 15 to 29, 1942, soil at field capacity..........................	20.0	90	80.0	6	98	..
	20.0	120	60.0	6	90	90
	20.0	150	48.0	6	99	..
	25.0	90	100.0	6	75	92
	25.0	120	75.0	6	75	..
	25.0	150	60.0	6	99	92

low compaction in the deeper cores indicates lack of structure of the type causing high permeability.

Plot results on this soil (table 8) show excellent control in February, August, and November at all dosages of 12.5 pounds or more. Dosages of 7.5 and 10.0 pounds were definitely insufficient in August. Spacing seemed unimportant, as did the brand of chemical used.

Results on Yolo clay loam treated in February, June, August, November,

and January were less impressive than on the coarser-textured soils. Air-flow studies are illustrated in figure 13. Though somewhat denser and less pervious in the top 12 inches, this soil had no high resistance strata; and it varied less throughout the profile than many.

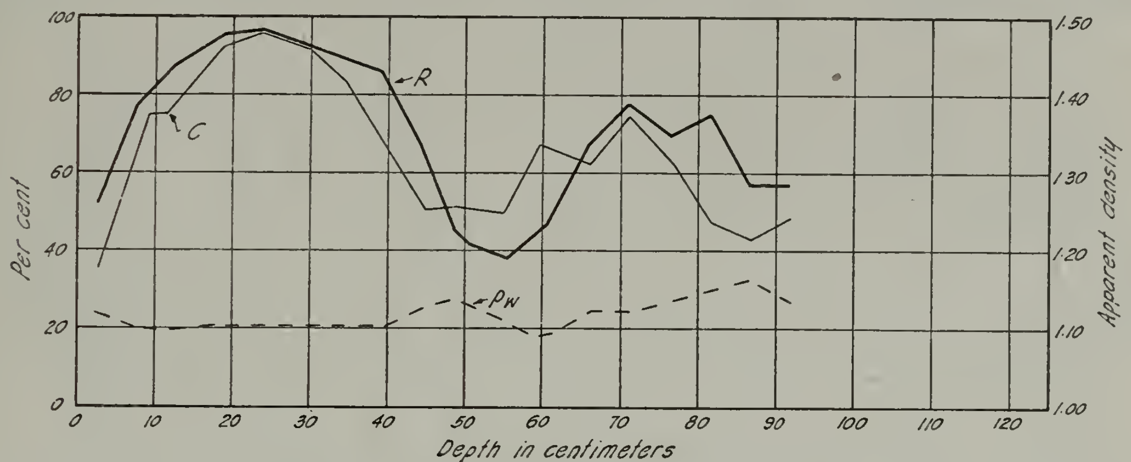

Fig. 22.—Changes in resistance to air flow (*R*), in compaction (*C*), and in moisture content (*Pw*) with depth in Yolo silt loam. Average of two columns. Compaction is expressed in units of density (grams per ml).

TABLE 10

Effect of Dosage, Spacing, and Depth of Injection of Carbon Disulfide under Different Conditions on Wild Morning-Glory in Yolo Silt Loam at Paicines

Date of treatment, and soil moisture	Method of treatment				Percentage kill, Anchor Brand
	Amount per square rod	Holes per square rod	Dosage per hole	Depth	
	pounds	*number*	*ml*	*inches*	*per cent*
Sept. 20, 1940, surface dry, moist below, fallowed field................	10	30	120	6	60
	10	60	60	6	35
	10	90	40	6	20
	15	30	180	6	100
	15	60	90	6	100
	15	90	60	6	100
	20	120	60	6	100
	10	60	60	10	80
	15	60	90	10	100
Aug. 26, 1941, dry in top 12 inches, moist below..........................	15	60	90	6	50
	15	90	60	6	95
	15	120	45	6	99
	20	60	120	6	50
	20	90	80	6	97
	20	120	60	6	99

The plot results (table 9), though less consistent than in coarser-textured soils, show certain significant relations. The lowest effective dosage, 15.0 pounds, was adequate only in June, whereas 20.0 pounds gave some good results at all treatment dates. Spacing results were inconsistent. Control with the two brands was not consistently different. Treatments were not very successful in August, when the topsoil was dry and cracked.

Yolo silt loam in Paicines, California, was studied. Figure 22 shows the air-flow results. This soil, loose and permeable in the top 2 inches (5 cm), was

denser and less permeable through the 2- to 10-inch (5- to 25-cm) cores, and then more permeable to a depth of about 24 inches (61 cm), where resistance rose through four fractions to drop again at about 3 feet (92 cm). The first dense region represents plow sole; the second resulted from stratified material of variable textures.

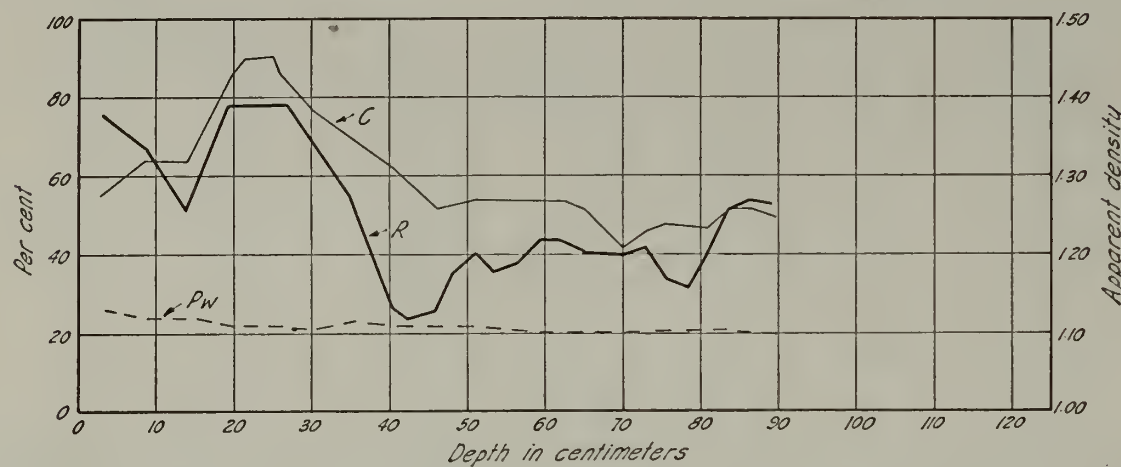

Fig. 23.—Changes in resistance to air flow (R), in compaction (C), and in moisture content (Pw) with depth in Yolo clay loam. Average of two columns.

TABLE 11

EFFECT OF DOSAGE, SPACING, AND DEPTH OF INJECTION OF CARBON DISULFIDE ON RUSSIAN KNAPWEED IN DRY YOLO CLAY LOAM, NEAR DIXON
(Treatment on September 20, 1941)

Depth and amount per square rod	Holes per square rod	Dosage per hole	Percentage kill	
			Anchor Brand	Activated
pounds	*number*	*ml*	*per cent*	*per cent*
6 inches:				
10	30	120	0	..
10	120	30	0	90
15	30	180	75	..
15	120	45	97	99
20	30	240	85	..
20	120	60	100	99

Plot results in table 10 show that 10.0 pounds was insufficient for satisfactory control. Either 15.0 or 20.0 pounds was excellent except on two plots with wide spacings. Correlation between spacing and effectiveness was good in the 1941 plots, 90 to 120 holes being required.

The Yolo clay loam plots at Dixon (table 11) were located in an infestation of Russian knapweed in an abandoned corner of an alfalfa field. Since the surface was dry and packed, carbon disulfide injection proved difficult. This explains the high resistance of the top core to air flow (fig. 23). Resistance dropped rapidly through two cores, rose to a maximum in the succeeding two, and then lowered to a minimum near 30 inches (76 cm). Compaction followed a similar course. As the plot results in table 11 indicate, 10.0 pounds was too small a dosage. Either 15.0 or 20.0 pounds was excellent with 120

injection points. Spacing makes a significant difference in finer-textured soil, more so than in the previous coarser-textured ones.

Figure 24 shows air-flow results on Dinuba sandy loam from Modesto. The samples, from a vacant lot, were impervious in the top two fractions, highly resistant in the 10- and 12-inch (25- and 30-cm) cores, and intermediate

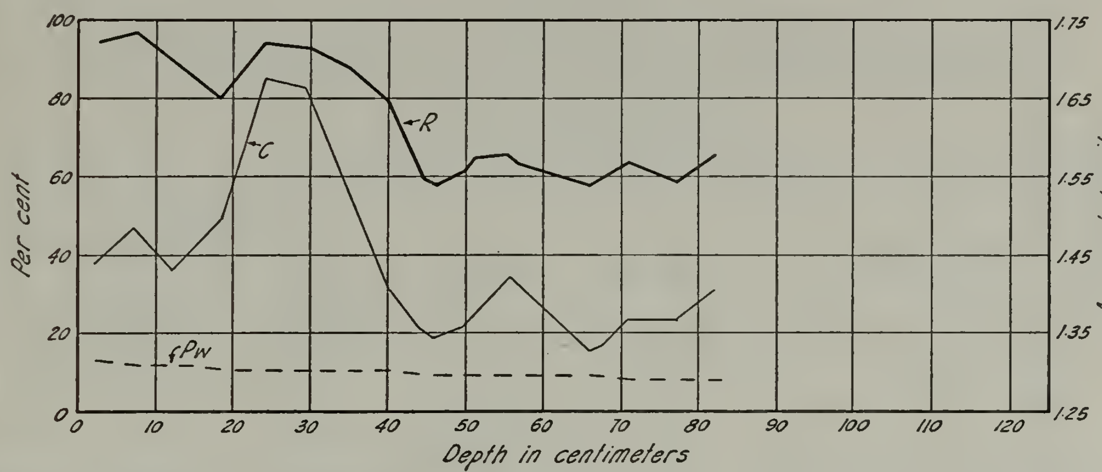

Fig. 24.—Changes in resistance to air flow (*R*), in compaction (*C*), and in moisture content (*Pw*) with depth in Dinuba sandy loam. Average of two columns. Because of the high density of this soil, the scale of apparent density, in grams per ml, has been shifted to bring the compaction curve into the range of the graph.

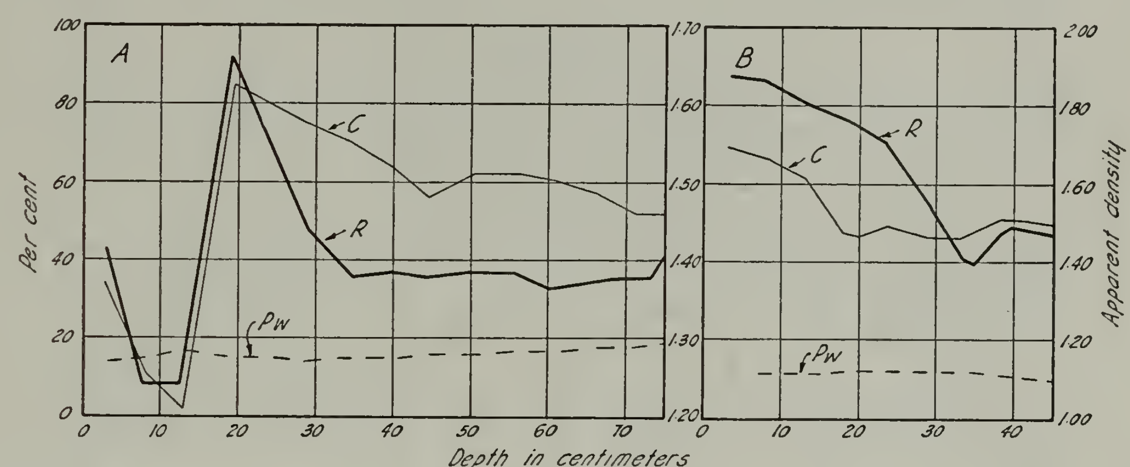

Fig. 25.—Changes in resistance to air flow (*R*), in compaction (*C*), and in moisture content (*Pw*) with depth in two California soils: *A*, Gridley loam; *B*, Greenfield coarse sandy loam. Resistance (*R*) and moisture content (*Pw*) for both graphs can be read from the percentage scale on the left. Note that the scales for apparent density, in grams per ml, are different for the two soils.

through the cores to a depth of 32 inches (82 cm). There was a hardpan layer at 3.5 feet (102 cm). Density in the plow-sole layer was 1.67 grams per ml, one of the highest values recorded. On September 1, 1941, plots in a morning-glory infestation on this soil were treated at a depth of 6 inches (15 cm) with 15.0 and 20.0 pounds of carbon disulfide. Two months later the maximum control was 25 per cent; and one year after treatment no effect was evident. This is an example of one type of soil that might require special methods to yield successful results with carbon disulfide.

Greenfield coarse sandy loam is a dense, gritty soil from granitic alluvium. The plots were located south of Salinas in a Sudan-grass pasture. As figure 25*B* shows, this soil had an apparent density of 1.69 grams per ml in the top

core, and the lowest density was 1.46 grams per ml. Resistance, although fairly high in the top layer, dropped throughout the top 14 inches (36 cm) to 40 per cent. As table 12 indicates, a 15.0-pound dosage was fairly effective at 120 holes per square rod, while 20.0 pounds proved successful at all three spacings.

TABLE 12

EFFECT OF DOSAGE, SPACING, AND DEPTH OF INJECTION OF CARBON DISULFIDE ON WILD MORNING-GLORY IN MOIST GREENFIELD COARSE SANDY LOAM

(Treatment on August 25, 1941)

Depth and amount per square rod	Holes per square rod	Dosage per hole	Percentage kill	
			Anchor Brand	Activated
pounds	*number*	*ml*	*per cent*	*per cent*
6 inches:				
15	30	180	80	..
15	60	90	90	..
15	120	45	95	80
20	30	240	100	99
20	60	120	99	..
20	120	60	100	100

TABLE 13

EFFECT OF DOSAGE, SPACING, AND DEPTH OF INJECTION OF CARBON DISULFIDE ON JOHNSON GRASS IN GRIDLEY LOAM; TOP SOIL DRY, WATER TABLE AT 30 INCHES

(Treatment on August 13, 1941)

Depth and amount per square rod	Holes per square rod	Dosage per hole	Percentage kill	
			Anchor Brand	Activated
pounds	*number*	*ml*	*per cent*	*per cent*
4 inches:				
15.0	120	45.0	75	..
20.0	120	60.0	90	96
4 inches:				
12.5	120	37.5	50	..
15.0	30	180.0	87	..
15.0	120	45.0	50	93
20.0	120	60.0	93	93

The Gridley loam was taken from an undisturbed area near the town of Gridley. This soil (fig. 25*A*) was firm but permeable in the top core, very light and loosely bound in the second and third cores—a condition caused by the presence of relatively large amounts of plant residues. Resistance and compaction both increased immensely in the 8-inch core because of an old plow sole, and then decreased gradually to intermediate values. Plots in Johnson grass were treated on this soil at the time indicated in table 13. The topsoil was dry and hard; there was 12 per cent moisture at 12 inches (30 cm), and the water table stood at 30 inches. Results were rather erratic, as shown by

readings taken one year after treatment; but the surviving rhizomes were confined to the top 4 inches (10 cm) of soil, from which they sent down roots and resprouted. Because of the plow sole, few roots had penetrated deeply, and these were killed. The live rhizomes could have been killed by shallow plowing, to make all treatments 100 per cent. The best results were obtained

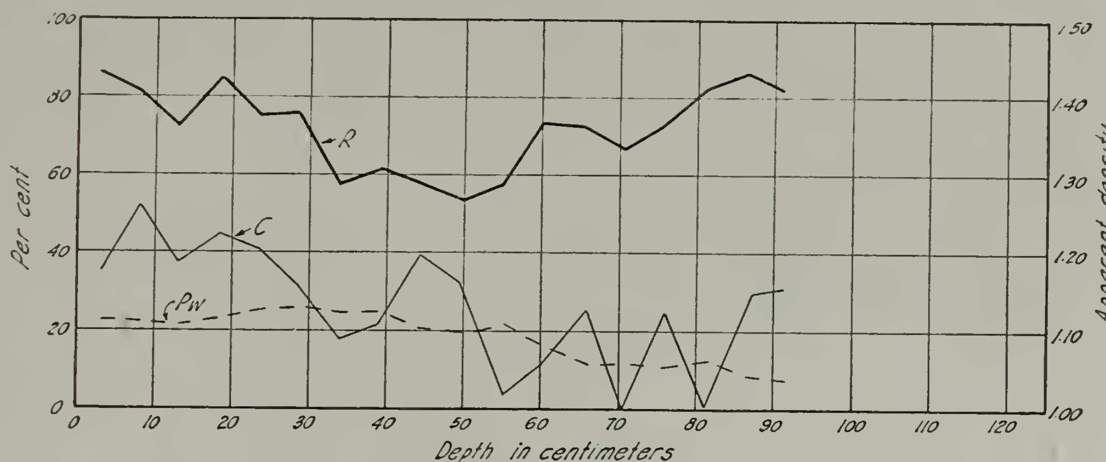

Fig. 26.—Changes in resistance to air flow (R), in compaction (C), and in moisture content (Pw) with depth in Hanford fine sandy loam. Average of two columns.

TABLE 14

EFFECT OF DOSAGE, SPACING, AND DEPTH OF INJECTION OF CARBON DISULFIDE ON WILD MORNING-GLORY IN DRY HANFORD FINE SANDY LOAM

(Treatment on August 12, 1941)

Depth and amount per square rod	Holes per square rod	Dosage per hole	Percentage kill	
			Anchor Brand	Activated
pounds	*number*	*ml*	*per cent*	*per cent*
6 inches:				
10.0	30	120.0	40	85
10.0	120	30.0	80	..
12.5	30	150.0	40	85
12.5	120	37.5	25	..
15.0	30	180.0	25	..
15.0	120	45.0	25	..
10 inches:				
10.0	30	120.0	60	..

with 20 pounds; there was no significant difference between Anchor Brand and "Activated" carbon disulfide.

Hanford fine sandy loam was studied at a location near Elk Grove. Figure 26 shows the air-flow results. Resistance, fairly high in the top core, dropped and rose again in the plow sole, lowered in the subsoil to a minimum at about 20 inches (50 cm), and rose again to a value as high as that in the top core. In the upper fractions, compaction followed resistance. In the lower ones, however, it fluctuated because of stratification with finely divided sediments that had little structure. Plot results (table 14) were poor in this soil.

Morning-glory infestations on a farm near Gridley were used in studies on

Honcut loam. Air-flow results (fig. 27) show that this soil was rather dense on top with a permeable layer beneath, then a dense impervious plow sole having an apparent density of 1.66 grams per ml, and below this a lighter, highly permeable subsoil. Treatments at 6 inches (15 cm) with 15.0, 20.0, and 25.0 pounds of carbon disulfide met with little success, presumably because of the highly compacted plow-sole layer. Had the plow sole been broken up

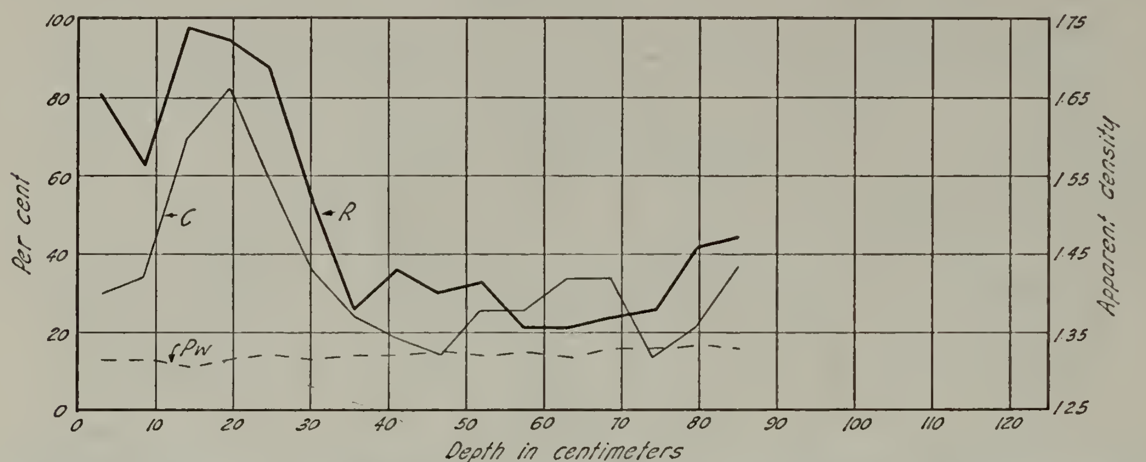

Fig. 27.—Changes in resistance to air flow (R), in compaction (C), and in moisture content (Pw) with depth in Honcut loam. One column.

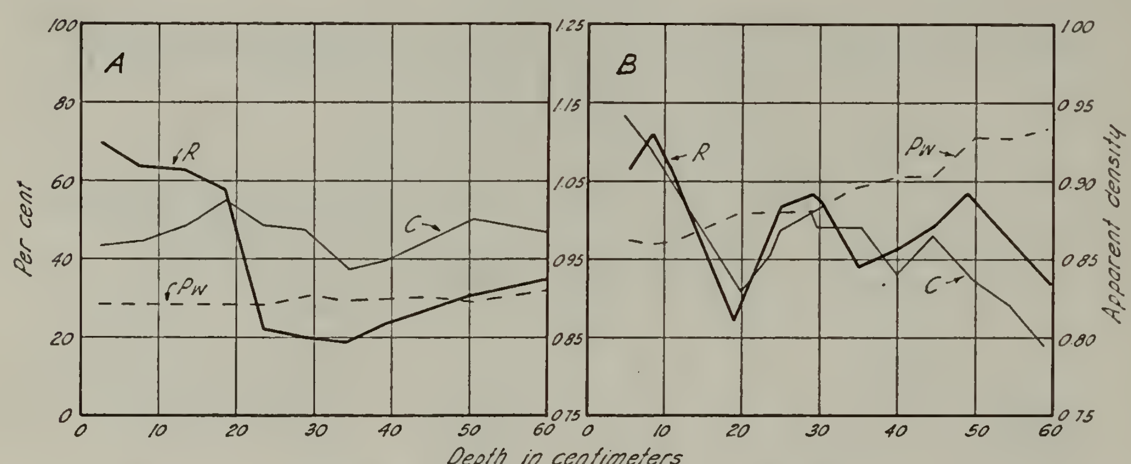

Fig. 28.—Changes in resistance to air flow (R), in compaction (C), and in moisture content (Pw) with depth in two California soils: A, Lockwood gravelly loam; B, Sacramento clay. Resistance (R) and moisture content (Pw) for both graphs can be read from the percentage scale on the left. The scales for apparent density, in grams per ml, are different for the two soils.

by subsoiling and the chemical placed beneath, the results would undoubtedly have been better.

Lockwood gravelly loam is an old alluvial soil lying west of the Salinas River, south of Salinas. As figure 28A shows, this soil had a well-developed plow sole even though the apparent density was low. Below the 10-inch (25 cm) level the soil was loose and permeable.

Treatments were put in at 6 inches (15 cm), with two plots at 10 inches (25 cm). Results (table 15) were not particularly successful, probably because of the plow-sole layer. At close spacing, 20.0 pounds gave 90 per cent control of the morning-glory, but 10.0 and 15.0 pounds were unsatisfactory.

Sacramento clay is a highly colloidal soil, rich in organic matter and having a large water-holding capacity. Figure 28B shows the air-flow results. Resist-

ance and compaction, starting at medium values in the top fraction, drop within the plowed layer, rise abruptly in the plow sole, which in this soil is between 10 and 14 inches (25 and 36 cm), and then descend, to rise again in a dense clay layer at about 20 inches (51 cm), and fall in a peaty layer at 24

TABLE 15

Effect of Dosage, Spacing, and Depth of Injection of Carbon Disulfide on Wild Morning-Glory in Lockwood Gravelly Loam; Soil Dry on Top, Moist Below

(Treatment on September 12, 1940)

Depth and amount per square rod	Holes per square rod	Dosage per hole	Percentage kill, Anchor Brand
pounds	*number*	*ml*	*per cent*
6 inches:			
10	30	120	40
10	60	60	60
10	90	40	60
15	30	180	70
15	60	90	70
15	90	60	75
20	120	60	90
10 inches:			
10	60	60	60
15	60	90	70

TABLE 16

Effect of Dosage, Spacing, and Depth of Injection of Carbon Disulfide on Hoary Cress in Sacramento Clay; Soil Dry on Top, Subirrigated Below

(Treatment on August 12, 1941)

Depth and amount per square rod	Holes per square rod	Dosage per hole	Percentage kill	
			Anchor Brand	Activated
pounds	*number*	*ml*	*per cent*	*per cent*
6 inches:				
15	30	180	90	..
15	120	45	93	85
20	30	240	80	..
20	120	60	98	95
25	30	75	99	98

inches (61 cm). The gradually increasing water content reflected soil moisture conditions above a standing water table at around 4 feet (122 cm). Plot results (table 16) show some increase in effectiveness with close spacing at the 15.0- and 20.0-pound dosages, success being achieved on most plots. Hoary cress was the weed treated.

Samples of San Joaquin sandy loam were taken from a grainfield near Montpelier. As figure 29 shows, the topsoil was coarse textured and permeable. Both resistance and compaction increased rapidly to a level near 10 inches

(25 cm), where a dense plow sole was present. Below this, resistance dropped for about 8 inches (20 cm) and then increased sharply, because of a very compact sandy clay overlying the hardpan. Apparent density, after remaining constant for 8 inches (20 cm) below the plow sole, increased sharply to 1.75 grams per ml, the highest value found for any soil in the studies.

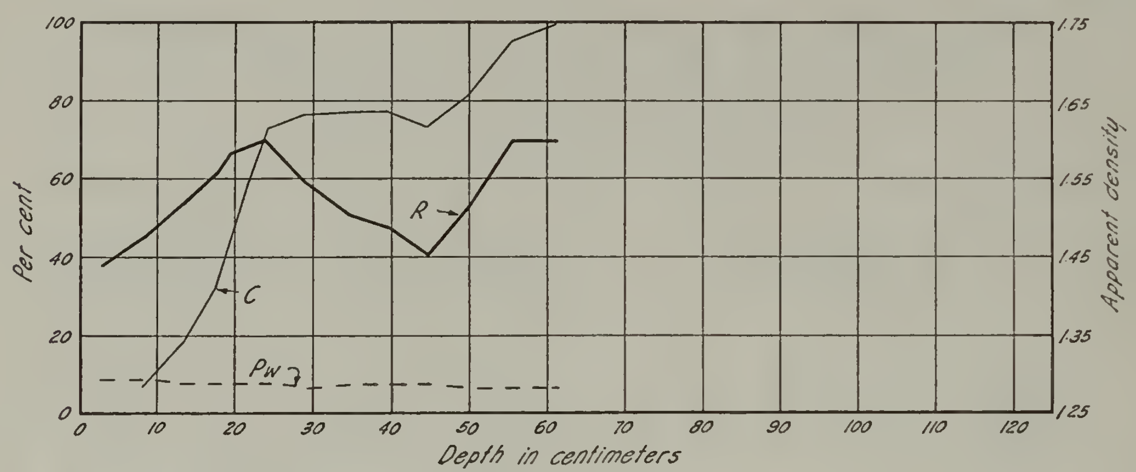

Fig. 29.—Changes in resistance to air flow (*R*), in compaction (*C*), and in moisture content (*Pw*) with depth in San Joaquin sandy loam. Average of two columns.

TABLE 17

Effect of Dosage, Spacing, and Depth of Injection of Carbon Disulfide on Wild Morning-Glory in San Joaquin Sandy Loam; Dry on Top, Moist Below

(Treatment on August 31, 1941)

Depth and amount per square rod	Holes per square rod	Dosage per hole	Percentage kill	
			Anchor Brand	Activated
pounds	*number*	*ml*	*per cent*	*per cent*
6 inches:				
12.5	30	150.0	50	..
12.5	120	37.5	25	25
15.0	30	180.0	60	..
15.0	120	45.0	50	25
20.0	30	240.0	85	50
20.0	120	60.0	70	..

Plot results (table 17) were unsatisfactory on this soil, probably because of the high compaction and low permeability. Wide spacing seemed better than narrow, but this difference may not be significant. The highly compact nature of the subsoil would make questionable the value of carbon disulfide treatment in this soil. Shallow-rooted weeds such as Bermuda grass and Johnson grass might be controlled.

Cores of Sorrento fine sandy loam, taken from a grainfield near Westley, were studied for compaction and resistance. In this soil the two curves (fig. 30) are similar and indicate a close correlation between permeability and density. There was a definite plow sole and, at about 32 inches (82 cm), a very dense layer with intermediate values between. Plot results in this soil were poor because the injections were made into loose, dry topsoil above a dense

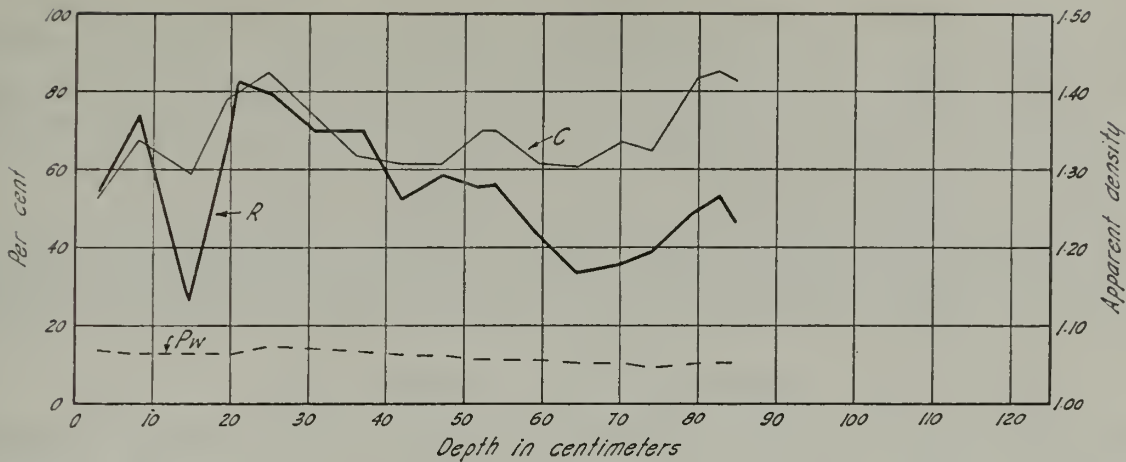

Fig. 30.—Changes in resistance to air flow (R), in compaction (C), and in moisture content (Pw) with depth in Sorrento gravelly fine sandy loam. Average of two columns.

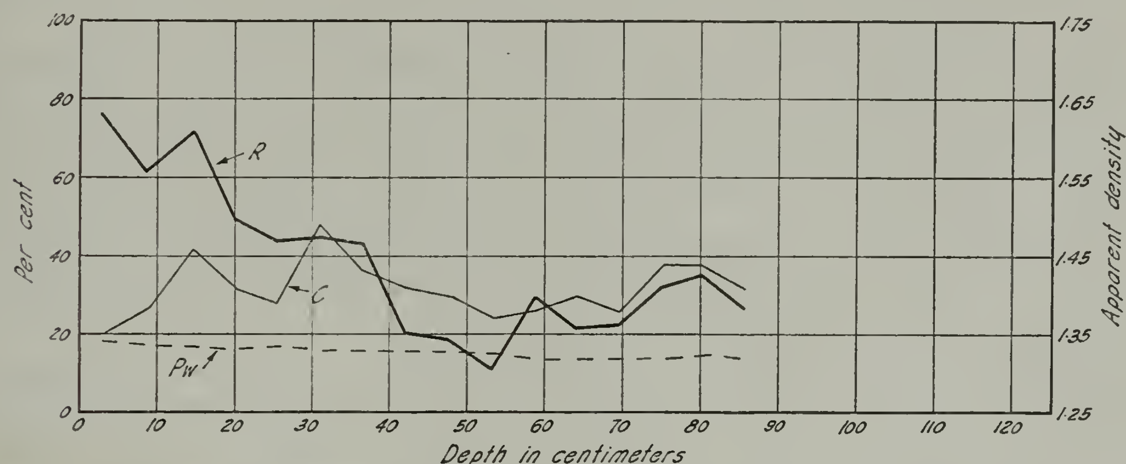

Fig. 31.—Changes in resistance to air flow (R), in compaction (C), and in moisture content (Pw) with depth in Wyman sandy loam. Average of two columns.

TABLE 18

EFFECT OF DOSAGE, SPACING, AND DEPTH OF INJECTION OF CARBON DISULFIDE ON WILD MORNING-GLORY IN WYMAN SANDY LOAM; DRY ON TOP, MOIST BELOW

(Treatment on September 10, 1941)

Depth and amount per square rod	Holes per square rod	Dosage per hole	Percentage kill	
			Anchor Brand	Activated
pounds	*number*	*ml*	*per cent*	*per cent*
6 inches:				
15	30	180	50	..
15	120	45	75	50
20	30	240	75	..
20	120	60	98	90
25	30	300	85	..
25	120	75	95	99

plow sole. A 20.0-pound plot with 30 injection points gave 90 per cent control. At 120 points the control was only 50 per cent.

The results of air-flow studies on Wyman sandy loam, a coarse-textured soil from basic igneous alluvium, are shown in figure 31. In this soil, resistance

was high, but compaction was low in the top fractions. Apparently, there were slick or compacted layers, probably caused by improper tillage procedures. After a rise at the 6-inch (15 cm) core—the depth to which this soil is periodically disked—resistance dropped to a very low value; but it rose again in the bottom 10 inches (25 cm).

The plot results (table 18) indicated a definite correlation with spacing, best control being found on the 20.0- and 25.0-pound plots with 120 injections. Under the conditions of treatment, 15.0 pounds was an insufficient dosage.

DISCUSSION OF RESULTS

Before the results of these experiments are reviewed, it should be pointed out that the object was to determine the effects of dosage, spacing, depth of injection, and the like, under varying soil conditions such as high and low soil moisture, presence and absence of plow sole, and variations in profile character. A high percentage of control was not necessarily sought.

Whereas the laboratory studies indicated that soil moisture was the predominating factor in controlling gaseous diffusion, air-flow and plot studies show that, in the field, soil structure is the major factor. Temperature determines the rate and extent of diffusion and enters the problem through its relation to spacing. There is some evidence that narrow spacings are required in cold soils, whereas wider spacing (with a consequent saving in application cost) may be used in summer when soils are warm.

Texture may sometimes be important. Very fine-textured colloidal soils apparently adsorb the chemical and require larger dosages. Field experience corroborates this conclusion, for 25 and even 30 pounds per square rod have been found necessary in treating some such soils.

Where a permeable structure is established, soil moisture seems to have little influence upon gaseous diffusion. However, because a dense plow sole may be rendered practically impervious by moisture approaching field capacity, soils having moist plow sole should not be treated unless the injections can be made through this dense layer. This requires deeper injection than is ordinarily recommended. Such deep treatment, however, must be followed by thorough compaction of the surface.

Moisture has a definite relation to surface sealing, since a recently sprinkled soil or one upon which rain has fallen is impervious. Moist surface soil may be tightly sealed by rolling or tamping, and losses from the surface thus prevented.

Judging from several of the plot tests, soils in which the surface layer is light and pervious, with increasing density in the subsoil, will present real difficulty; but a soil with a dense surface layer and decreasing density with depth may be treated with much more assurance of success. Where the structure provides for ready diffusion of gas into the subsoil, 15 or even 10 pounds per square rod has proved satisfactory (see data in tables 6, 7, and 8). Such soils are usually coarse to intermediate in texture and capable of surface compaction for sealing. Spacing in them may usually be widened, with considerable saving in application cost. In all soils, localized regions of restricted permeability should be subsoiled or deep plowed and then thoroughly packed, particularly on the surface, to provide a proper seal.

In fine-textured clay and adobe soil types, use of carbon disulfide in weed control should be preceded by plot studies to determine the adaptability to treatment. Some such soils, if reduced in moisture content by growing a vigorous crop, and then plowed and disked thoroughly to produce a deep mulch, may be treated with success when dry. With others it has proved best to proceed as in preparation for seeding in the spring and, maintaining the mulch, to treat with carbon disulfide as soon as the soil becomes warm, in early summer. Even fine-textured soils of the more fertile types have sufficient structure to be pervious to vapor while moist; in these, the obtaining of proper conditions for surface sealing is more important than reducing the soil moisture content. If the drying of a fine-textured soil into clods makes it impracticable to prepare a dust mulch, then treatment of the moist soil is the most feasible procedure. Where a water table maintains a high content of soil moisture in the subsoil, one should try carbon disulfide with caution on a small scale before using it in quantity.

Depth of injection is another problem that must be related to local conditions. In general, the deeper the treatment the less the surface loss. This rule, however, must be interpreted to meet each situation. If the weeds have shallow roots, and the topsoil is moist, and the injection is very deep, resprouting may be expected. Under these circumstances, treatment to a depth of only 4 inches has been suggested. Such treatment, however, is bound to suffer surface loss. Where possible, it seems better to inject 6 inches deep or deeper, and to destroy resprouting crowns by plowing, disking, cultivating, or knifing after the deeper roots have been killed; in fact, such a practice is recommended in some regions. In dry topsoil the rule is to treat as deeply as convenient, not to exceed 16 inches. In such cases there should be a dust mulch to prevent surface loss.

PRACTICAL USE OF CARBON DISULFIDE

As was stated in the Introduction, carbon disulfide has long found practical use in controlling perennial weeds. This bulletin aims to describe clearly the various factors that determine the effectiveness of this chemical and to point out certain limitations. Physiological studies have been discussed, and soil investigations described in detail.

Season of Application.—According to tests the optimum season for applying carbon disulfide is summer, especially in regions of very cold winters and wet heavy soils. Admittedly, results with the standard dosage are satisfactory at any season (p. 5) in the more temperate climates, and successful control has followed injection even through a layer of frozen soil. Comparative tests on one soil throughout the year show, however, that less chemical is required in summer. Where the standard dosage has produced satisfactory results in cold soils, these experiments indicate that lower dosages could be used with equal success in warmer seasons. On the other hand, if labor shortage or adverse soil conditions prevent application in summer, then fall, spring, or even winter treatment may be used, the dosage being increased to meet the situation.

Dosage in Relation to Soils and Soil Type.—Table 19 gives the relations between dosage in terms of milliliters per injection, spacing, and over-all dosage in pounds per acre. Calculations were based upon a density of 1.26 grams per ml for liquid carbon disulfide at 20° C.

TABLE 19

DOSAGE-SPACING VALUES FOR CARBON DISULFIDE

Radius of effective penetration	Distance between*		Injection points			Carbon disulfide—per injection									
	Rows of injection points	Injection points in rows	Per square foot	Per square rod	Per acre	15 ml	30 ml	45 ml	60 ml	90 ml	120 ml	150 ml	180 ml	210 ml	240 ml
inches	*inches*	*inches*	*number*	*number*	*number*	*pounds per acre*	*pounds per acre*	*pounds per acre*	*pounds per acre*	*pounds per acre*	*pounds per acre*	*pounds per acre*	*pounds per acre*	*pounds per acre*	*pounds per acre*
8	12.0	13.9	0.866	236.0	37,725	1,576	3,151	4,726	.....	.....	.....	.....	.....	.....	.....
9	13.5	15.6	0.684	186.0	29,808	1,245	2,490	3,734	4,979	.....	.....	.....	.....	.....	.....
10	15.0	17.3	0.554	151.0	24,144	1,008	2,016	3,025	4,033	6,049	.....	.....	.....	.....	.....
12	18.0	20.8	0.384	104.0	16,767	700	1,400	2,101	2,801	4,201	5,601	.....	.....	.....	.....
14	21.0	24.2	0.282	76.8	12,318	.....	1,029	1,543	2,058	3,086	4,115	5,144	.....	.....	.....
16	24.0	27.7	0.217	59.1	9,431	.....	788	1,182	1,575	2,363	3,151	3,938	4,726	.....	.....
18	27.0	31.2	0.171	46.5	7,452	.....	.....	934	1,245	1,867	2,490	3,112	3,734	4,356	4,979
20	30.0	34.6	0.139	37.8	6,036	.....	.....	.....	1,008	1,512	2,016	2,521	3,025	3,529	4,033

* For efficient spacing of injections the injection points should be placed at the corners of equilateral triangles. For such spacing of points in rows the distance between points within a row corresponds with the base of the triangle; the distance between rows represents the altitude of the triangle. (For a detailed discussion of the placing of soil fumigants, see Taylor, 1939.)

A gallon of carbon disulfide weighs approximately 10.5 pounds. The standard dosage (p. 5) is equivalent to about 2 gallons per square rod, which is approximately 20 pounds (3,200 pounds per acre). Most fertile agricultural soils have good structural characteristics—that is, adequate pore space pervious to gas. With them, accordingly, the effect of soil texture upon diffusion need not be considered. Texture, however, determines adsorption and hence has a direct bearing on dosage. According to the plot experiments previously described, carbon disulfide may give satisfactory results on coarse-textured, open soils with as little as 10 pounds per square rod. In fine-textured soils the standard rate of 20 pounds will be required, particularly if the subsoil tends to be dense or very moist. This rate will be necessary in coarse-textured soils treated in winter or in an excessively moist condition.

Dosage in Relation to Soil Moisture.—As already indicated (pp. 14 and 21), soil moisture may be important in carbon disulfide treatment. Moist soils can be successfully treated, but only if the operator carefully considers soil moisture conditions in determining dosage and depth.

In general, warm, dry soils are most favorable for the use of carbon disulfide. This statement presupposes, however, that surface sealing is adequate. When the topsoil is dry, injection should be as deep as practicable (about 12 inches or 30 cm), and there should always be a dust mulch. Treatment to any depth through open clods will fail.

If the topsoil is moist, injection should be at such depth that the crowns are killed; otherwise the crowns should be plowed, disked, or scalped before they can reinfest the area. Deep treatment, with subsequent killing of crowns, minimizes surface loss and reduces the dosage needed.

A dense plow sole that turns up cloddy if plowed dry may have to be broken while the soil is still moist and then worked down with the disk, harrow, and packer. Treatment may well be made to a depth of 8 inches or more, for the plowing and disking usually kill crown growth of weeds.

Dosage in Relation to Compaction.—As the experiments have shown, any compacted layer restricts carbon disulfide diffusion. This is the reason for tamping or rolling the surface to prevent excessive surface loss. Where dense plow or cultivator soles exist, the treatment should be made through this layer; or the layer should first be broken up. Injection through a dense sole is practically impossible with the hand applicator, but may be accomplished with the tractor-drawn subsoiler. Great care should be exercised; the surface must be thoroughly sealed behind the applicator. When the subsoiler is drawn through tough, refractory sole that is fairly dry, the cloddy soil can be worked down only with difficulty.

Hardpan layers are usually dense enough to restrict root growth as well as to hinder gas diffusion. For this reason they usually do not affect carbon disulfide treatment. When, however, they cause a perched water-table condition in irrigated soil, they may prevent success.

Effect of Wind on Carbon Disulfide Treatment.—As much field experience has proved, heavy wind tends to bring about excessive surface loss of carbon disulfide and hence to reduce materially the effectiveness of treatment. In moderate wind, deep injection with good surface sealing should be used. The work should not be attempted in very windy weather.

Response of Different Perennial Weeds.—Various weed species show differing susceptibilities to carbon disulfide treatment. According to careful analysis of field-plot results, the major differences in response may relate to variations in soil requirements and root distribution more directly than to inherent differences in cellular behavior. It is difficult to retain a high vapor density of carbon disulfide in the top 4 inches of soil. Accordingly, if the perennial portions of the underground structures of a weed are largely restricted to this surface layer, killing may be difficult even though the cells are just as subject to the toxicity of the vapor as the cells of more easily killed species. Bermuda grass is such a weed. Uniform distribution of the vapor throughout a mass of wet clay soil is, likewise, seldom achieved. For this reason, it may be almost impossible to destroy species that characteristically inhabit such soil—hence, perhaps, the seeming difficulty in killing hoary cress in fine-textured soils. Camel thorn (*Alhagi camelorum* Fisch.) also has proved resistant to carbon disulfide. This pest often inhabits dense clay soils of saline character and resprouts from laterals at depths of 4 to 5 feet. The problem may be one of vapor distribution, not of any specific ability to tolerate carbon disulfide.

Bermuda grass, nutgrass (*Cyperus* spp.), and other relatively shallow-rooted weeds have been hard to control with carbon disulfide in lawns, in sandy soils, or wherever the root distribution requires shallow treatment. One way of handling this situation has been to inject the chemical to a depth of only 2 or 3 inches and immediately cover the area with wet canvas or vapor-proof building paper. This covering is sealed at the borders of the infestation by burying it in a trench and covering it with soil. To prevent escape of the vapor the canvas must be kept wet, or the building paper must be sealed at the edges or lapped. Covering quickly with 2 to 4 inches of soil has also proved effective. Although this expensive method is applicable only to small areas, it will control patches of noxious weeds in lawns and golf greens where the only other possibilities would be complete soil sterilization or removal of the infested soil to a depth of 12 inches or more.

Problems of Reinfestation.—One problem inherent in the use of most temporary soil sterilants is that of reinfestation by seedlings. Usually, sometime during the development of a serious infestation, a seed crop has been allowed to mature; and often a succession of seed crops have been plowed under or worked into the soil, where most weed seeds will remain viable for several years. Such seeds, if returned to the surface by subsequent plowing, will germinate. After carbon disulfide is injected, therefore, every effort must be made to prevent reinfestation. A few rules should be followed: (1) keep such areas in intertilled crops as long as feasible after treatment; (2) avoid deep plowing, but cultivate, and watch the area very closely, killing all seedlings of perennial weeds even if hand-hoeing or pulling within the crop rows is required; (3) avoid such crops as small cereals, grain hay, and flax, which allow reinfestation in the spring and early summer while ripening for harvest; (4) if the land is needed to produce feed, use alfalfa, Ladino clover, or some similar crop that tends to hold weeds in check through shading and competition.

All uncropped areas (for example ditchbanks, roadsides, and fence lines) should be watched carefully to prevent seed growth. Often such areas should

be treated with a permanent soil sterilant if they cannot be mowed or periodically sprayed. Only a complete and comprehensive program of control can eradicate deep-rooted perennial weeds, and only a program aimed at eradication will justify the use of carbon disulfide.

Economics.—The practicability of using a weed-control method that costs over $100 an acre has often been questioned. On the other hand, past and present use of hundreds of carlots of carbon disulfide proves that the method is feasible in many places. Obviously there are situations where the expense would not be justified. Just as obviously, there are many places where carbon disulfide is the best and most practical chemical to use.

Large acreages of densely infested land will seldom bear the cost of such treatment unless they can be immediately cropped with beans, cotton, vegetables, or seed crops that render a quick cash return. Cropping and tillage methods are available for reducing the density of large infestations to a point where chemicals can be used to clean up the areas. (For discussion of such methods see : Ball *et al.*, 1940.) After cropping or tillage programs, small local infestations of deep-rooted perennials may survive unobserved in the field, along fences, ditches, headlands, and in other out-of-the-way places. These immediately act as sources of reinfestation; if left uncared for, they may spread and return the area to its original weedy state. For such a situation carbon disulfide is an ideal herbicide: it quickly kills the weeds and permits almost immediate use of the land.

Though carbon disulfide may be utilized in a program of large-scale weed control, probably its most practical use is to prevent the spread of deep-rooted perennials in the early stages of infestation. Many thousands of acres of highly productive land have only small scattered infestations of wild morning-glory, Russian knapweed, hoary cress, or other noxious perennials. Where beans, cotton, melons, corn, vegetable and seed crops are being produced, these infestations not only reduce yields, but act as sources of seeds and root pieces for constant increase. Under such conditions carbon disulfide is the most valuable herbicide available: it can be applied at almost any stage in the crop-production program, it leaves no poisonous residue on the crop or in the soil (except as mentioned in footnote 2 and explained on p. 51); and the land can be returned to use in a minimum of time. The expense should be levied, not against the actual areas of infestation but against the total acreage jeopardized. Used in this way, carbon disulfide is probably the most valuable herbicide for combating perennial weeds.

Effects upon the Soil.—An application of 20 pounds of carbon disulfide per square rod is equivalent to 3,200 pounds per acre. Of this, 84 per cent, or about 2,700 pounds, is sulfur; and, though some of this is lost by diffusion, the bulk is retained and oxidized to sulfuric acid, which dissolves bases and is converted to sulfates. For this reason carbon disulfide tends to correct alkalinity, and renders some soils more fertile than before treatment.

Being poisonous, carbon disulfide has a distinctly toxic effect upon soil organisms such as nematodes, wireworms, and bacteria. This amounts to a temporary partial sterilization, which usually favors subsequent growth of higher plants. Furthermore, with the death and decay of the roots of deep-rooted perennial weeds the soil is left permeable to moisture and is well

aerated. Crops on areas treated with carbon disulfide are distinctly better than those on adjacent untreated areas. Figure 32 illustrates this result with barley. Pure carbon disulfide has no known deleterious effect upon the soil.

Although this bulletin considers carbon disulfide only in connection with weed control, the chemical is invaluable in treating phylloxera of vines, armillaria root rot (oak root fungus) of trees and vines, and other soil pests. It is being applied before the replanting of orchards and vineyards where trees or vines have died. It is also widely used as a fumigant and poison in controlling insects and rodents.

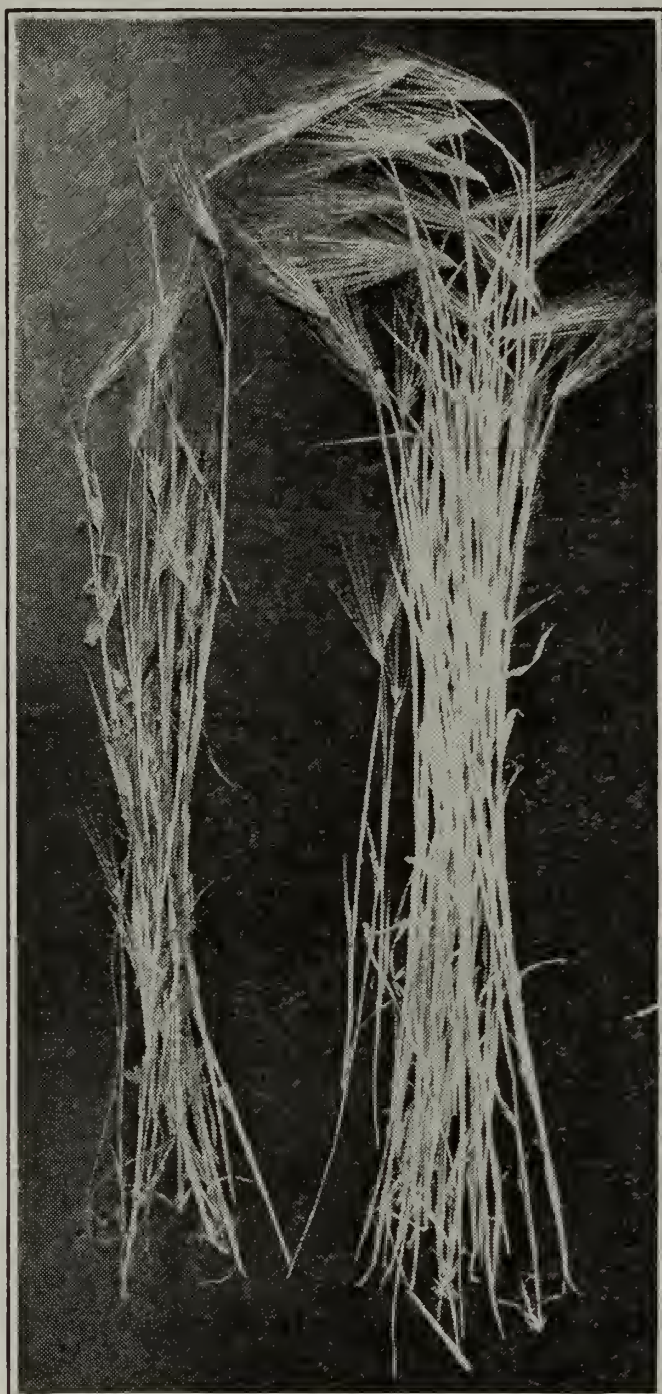

Fig. 32.—Right, barley from carbon disulfide treated land; left, barley from a similar area that was not treated. (From Robbins, Crafts, and Raynor, *Weed Control,* by permission of McGraw-Hill Book Company, copyright owners.)

Brands of Carbon Disulfide.—As already mentioned,[17] there are two brands of carbon disulfide. Anchor is a clear, colorless form, relatively pure, whereas "Activated" is a reddish liquid containing a chemical amendment that reduces its vapor pressure. Developed to minimize vapor losses from the soil surface, this latter form may be the more effective of the two in warm, dry soils; and it may allow a somewhat shallower injection because it develops less pressure in the soil and consequently has less tendency to leak through the surface seal. On the other hand, it tends to stay in the soil longer than Anchor and may delay planting of crops after treatment. The chemical amendment used in "Activated" carbon disulfide is itself toxic and may temporarily sterilize the soil against the growth of annual weeds. Applied during fall, the "Activated" form has been known to render treated soils toxic to annual weeds throughout the following winter.

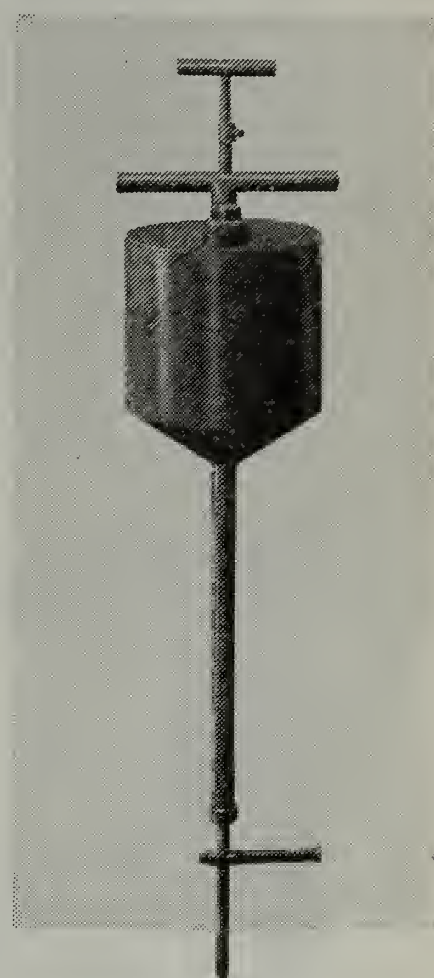

Fig. 33.—Hand prod for applying carbon disulfide. By raising and then pushing down on the top handle, a measured charge of liquid is forced into the soil through holes at the tip of the prod. (Courtesy of Wheeler, Reynolds & Stauffer.)

Methods of Application.—During the time carbon disulfide has been used in weed control, many methods of applying it by hand have been devised. Early workers made holes by driving iron rods into the soil; they poured the liquid chemical into the holes through funnels. Improvements on this method have involved use of a prod with a stirrup to enable the operator to remain standing. Use of this instrument, however, is limited to moist soils. Another method involves an electric drill with a long shank. Funnels have been extended for use in a standing position; and one such funnel has been fitted with a small 2-fluid-ounce measuring cup, which, upon being filled, can be tipped directly into the throat of the funnel. A long-spouted teakettle has proved as handy as any other container for handling the liquid.

Another hand method, mentioned in the early literature and still utilized, especially in the sod of grass pastures, is to force a spade or shovel to full depth of the blade into the soil and then to push forward on the handle, forming a crack between the blade and the soil. The liquid carbon disulfide is poured down this crack, whereupon the blade is removed and the soil tamped firmly.

The most popular hand method now practiced makes use of the Mack Anti-Weed gun. This applicator (figure 33) consists of a hollow prod, a gallon container, and a piston pump with adjustable stroke for measuring the charge. The end of the prod is hollow, with many small perforations just above the tapered point. First, the prod is forced into the soil by means of the foot stirrup. Next, the handle is pulled up, filling the pump with carbon disulfide.

[17] See footnote 2.

Then the handle is pushed down, forcing the liquid out into the soil through the perforations near the point. The collar, with its set screw on the handle shank, can be set to deliver any amount of carbon disulfide up to somewhat

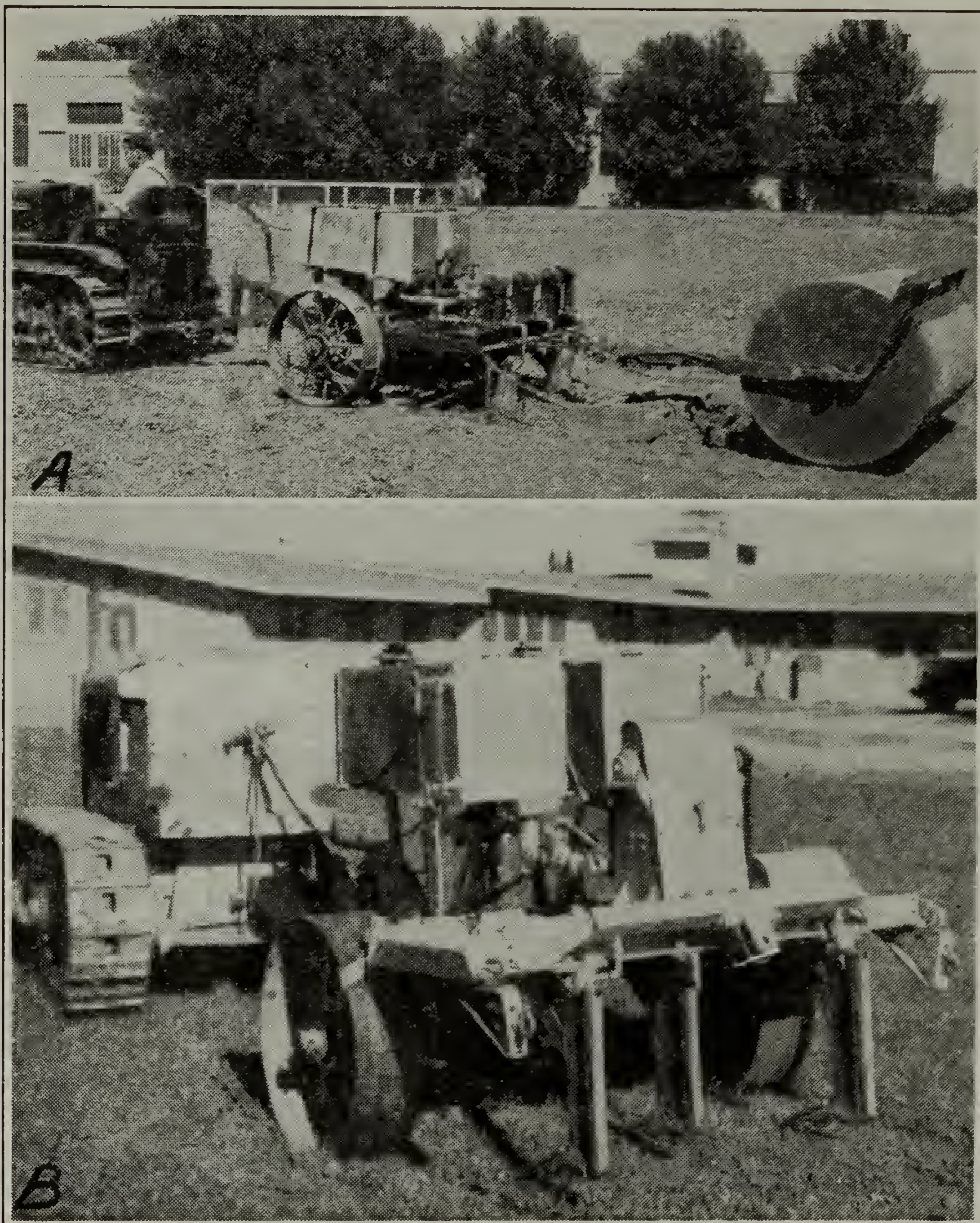

Fig. 34.—*A*, Complete equipment for power application of carbon disulfide in weed control. The drag behind the subsoiler fills the furrows left behind the standards, and the water-filled roller packs the soil. *B*, Detailed view of improved applicator. Liquid from the tanks is metered through three pumps and delivered by force to the tubes at the rear of the subsoiler standards. The pumps of this applicator are made of stainless steel to resist corrosion. (Courtesy of Wheeler, Reynolds & Staffer.)

more than 2 fluid ounces. One important precaution is to wash the machine out thoroughly with kerosene, diesel fuel, or light lubricating oil after use each day. If it is left full of carbon disulfide or empty without washing, the pump and valves will corrode, and the apparatus will be ruined.

Early machine application was made with a subsoiler to which was attached a tank with a small delivery tube running down behind the subsoiler standard.

Calibration was done by setting a valve in this outlet line. Such a machine had two faults: First, the dosage varied somewhat with the height of liquid in the tank. This variation was compensated for somewhat by altering the speed of the machine, but calibration could not be accurate. Second, application was continuous; if a fire occurred, as occasionally happens when the subsoiler strikes a rock and makes a spark, the whole application was liable to be lost.

Improvements on this machine have involved the use of positive-acting metering pumps, which, running off the wheels of the subsoiler, discharge measured volumes of carbon disulfide at the desired intervals. Dosage is not affected by the level of liquid in the tank, nor by the speed of travel of the machine. One such apparatus is illustrated in figure 34. This machine has three standards and will cover up to 4 acres per day. The surface is sealed by the drag and water-filled roller shown in figure 34*A*.

Proper spacing of injection points, where applications are made by hand, has been accomplished by various means. One method has been to use guide lines of wire, marked by placing drops of solder at the proper intervals; or rope lines marked by binding with twine or dark thread. Four lines are used: two head lines to space the rows, and two work lines to space the injection points in the rows. The two head lines are stretched parallel, at a distance equal to the length of the work lines. The first work line is stretched between the head lines with the knots or markers adjacent to those at the ends of the head lines. The second work line is stretched between the second markers on the head lines, but with one head-line marker lying halfway between the first and second marker of the work line. This gives the staggering required to place the injections at the vertices of a triangle rather than at the corners of a square. Such spacing has proved, from long practice, to be best. Usually, according to the plot tests reported in this bulletin, the small difference in spacing represented by this staggering of the injections is of little significance. It probably is needed, however, to take care of the occasional situation where the dosage might be just on the border line of sufficiency. Particularly is this true where wider spacings and lower dosages than standard are used.

Other methods of spacing involve, for example, the use of markers (as in planting row crops) or the use of marked rods. Convenience is the main consideration, and no one method has proved best under all circumstances.

After an application by any method, the soil should be compacted to form a seal. Where the work is done by hand, the operator should close the hole by pressing the soil down with his heel. After treatment, a garden rake should be used to fill in the holes and cracks, and the area rolled as in sowing a lawn.

Where large areas are being prepared for carbon disulfide application, plowing followed by thorough disking will provide the mulch needed to make possible a proper sealing by rolling. If the topsoil is dry, the disking should be at least 10 inches deep; and the soil should be worked sufficiently to provide a dense dust mulch. Such preparation should be done several weeks before application because time must be allowed for regrowth of the weeds. Plowing or disking immediately before treatment scatters root segments, many of which might escape notice if not allowed to sprout.

Precaution.—Carbon disulfide vapor is inflammable and burns with a scarcely visible blue flame. Since a mixture of the vapor with air is explosive,

the liquid must be handled carefully. Empty drums containing this explosive mixture are particularly dangerous. The combustible vapor of carbon disulfide may be ignited by the discharge of static electricity generated by the motion of a rubber-tired vehicle. A man walking through stubble or across a dry, cloddy field may generate enough electricity to cause a spark as he touches the bung or spigot on a drum. The operator should ground each drum from which the chemical is to be withdrawn, by placing a chain across it with one end buried in the ground. Even the flow of the liquid from a spigot has caused a spark and ignited the vapors and liquid. Smoking must be prohibited while working with or near carbon disulfide.

As is evidenced by its use in fumigation, the vapor is poisonous. It should not be inhaled, and all handling of the liquid for weed control should be done out of doors.

SUMMARY

Carbon disulfide is a volatile liquid widely used for controlling deep-rooted plants. When injected into the soil it forms a toxic gas, which permeates the pore spaces and renders the soil atmosphere poisonous to plant roots.

The standard treatment, evolved over the years, is to inject 2 fluid ounces of liquid in holes 18 inches apart each way to a depth of 6 to 8 inches.

Effectiveness of this herbicide is determined by many factors, mostly related to the soil. Rapid diffusion of the gas is favored by high soil temperature, low moisture content, and loose, open structure. Of these factors, structure (under most field conditions) predominates.

To prevent losses of the vapor from the surface is just as essential as to obtain uniform distribution through the soil. For this reason, the surface soil is sealed after an injection. Compaction by rolling and tamping is part of the standard procedure. Treatment followed by sprinkling or made after early fall rains is also common.

Application methods depend on the soil relations mentioned above. Depth of injection depends upon soil moisture, which affects sealing, and upon weed species. Shallow injection is used where the surface soil is moist and can be effectively sealed; deep injection where the topsoil is dry. Effective mulching is necessary in dry soil.

Spacing of injection points and dosage are interdependent. Wide spacing is economical, but only under favorable conditions of soil temperature and structure can the distance be greater than the standard 18 inches. Where conditions are adverse, spacing may be as close as 12 inches.

Dosage on an area basis is determined by soil type and structure, weed species, and the conditions that determine sealing. Warm, coarse-textured, pervious soils that can be effectively sealed may require only 10 pounds per square rod, or 1,600 pounds per acre—just half the standard amount. In moist, fine-textured soils and under adverse temperature conditions, dosage may be increased to 25 or even 30 pounds per square rod. Under such conditions the 2-ounce injection is usually retained, but the spacing is reduced.

Though carbon disulfide has been used with success at all seasons, summer is the most favorable time from the standpoint of soil temperature and moisture.

Plow sole is the commonest soil structure that interferes with the treat-

ment; if dense and wet, it may be almost completely impervious to the vapor. As a rule, the plow sole should be broken up before application. Where this cannot be done, soil moisture should be reduced by growing a vigorous annual crop, and injection should place the liquid on top of the dry sole beneath at least 10 inches of well-pulverized dust mulch. Treatment through a mass of open clods is useless.

Hardpan because of its position does not interfere with weed control by carbon disulfide, for hardpan that can be penetrated by roots is usually pervious to the gas; one that cannot be penetrated prevents downward diffusion and intensifies the killing action.

Carbon disulfide should not be applied during heavy wind. Light wind does not interfere if the surface sealing is adequate.

Different weed species respond differently to carbon disulfide, primarily because of different soil requirements and root distribution of the weeds. Hoary cress in wet, fine-textured soils or in peat is hard to control. Camel thorn, in addition to habitating clay soils, is deep-rooted. Bermuda grass, nutgrass, oxalis, and other shallow-rooted weeds require special methods. After shallow injection or sprinkling on the surface, such weeds are covered with gastight paper or wet canvas that is covered with soil at the edges. Another method, often used with wild morning-glory in moist soils, is to inject to a depth of 4 inches, sealing the surface carefully. After the deep roots have been killed, any surviving crowns are destroyed by scalping, disking, or knifing, followed by thorough cultivation. Such a treatment may be necessary even after injection to 6 or 8 inches if the topsoil remains moist.

Carbon disulfide may be applied by several hand methods, such as the use of the Mack Anti-Weed gun; or by machine, using a modified subsoiler.

Though seldom justified in very large-scale weed control, prompt use of carbon disulfide is recommended to prevent the spread of small infestations; for cleanup after large-scale cultural or cropping programs; and for general use around gardens, nurseries, landscaped areas, and the like. For such purposes it is the most effective herbicide for controlling deep-rooted perennial weeds. It has proved invaluable in large areas devoted to beans, and to vegetable and seed crops where weeds annually cause heavy losses if not controlled.

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